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SPRING RUN-OFF AND NUTRIENT-SEAWATER DENSITY CORRELATIONS IN THE MASSACHUSETTS BAY

PART I.

by

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and

Robert C. Beardsley

PART II.

by

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Report No. MITSG 74-9

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PART II. DISSOLVED NUTRIENT-SEAWATER DENSITY CORRELATIONS AND THE CIRCULATION IN BOSTON HARBOR AND VICINITY

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ABSTRACT - PART I

SPRING RUN-OFF INTO MASSACHUSETTS BAY, 1973

BY

VESHPATI MANOHAR-MAHARAJ

AND

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The mean salinity over the depth for the water in Massachusetts Bay from Cape Ann to Cohasset Harbor was computed at different times in the spring of 1973 to obtain the amount of fresh water in the Bay. This volume was then compared with the volume of fresh water coming into the Bay by way of rivers and of the Deer Island sewage treatment plant.

The volume of fresh water in the Bay and the influx of fresh water from spring run-off were found to compare quite well. The maximum amount of fresh water in the Bay was 2,450 million cubic meters on May 25, 1973. The major loss of fresh water from the region considered during the spring seemed to be diffusion of salt into the Bay rather than advection of fresh water out of the Bay. It was also shown that the Merrimac River accounted for about 90% of the volume of fresh water found in the Bay.

PART I

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This report was prepared by Mr. Veshpati Manohar-Maharaj, research assistant and Dr. Robert C. Beardsley, Associate Professor of Meteorology. The contributions in the data collection process by Messrs. J. Vermersch, E. Firing and C. Young, and in the data processing by Messrs. B. Laird, C. Young, and staff members of the Lincoln Laboratory, are gratefully acknowledged. The manuscript was critically reviewed by Mr. B. Butman, Mr. D. Bumpus, and Dr. Bryan R. Pearce. Mr. S. Ricci drafted the figures and Ms. Stephanie M. Demeris typed the manuscript.

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CHAPTER 1

INTRODUCTION

Although as early as 1927 Bigelow did extensive studies of the Gulf of Maine, no detailed study was performed in Massachusetts Bay. Since Bigelow's study (1927), more work has been done on the whole continental shelf of the Eastern coast of North America, but these studies were primarily concerned with the current patterns for the region: Day (1958), Bumpus (1961), and Graham (1970). The only extensive salinity and temperature measurements in Massachusetts Bay have been at the Boston Lightship Chase (1969).

Butman (1972) modelled a flow of fresh water into a two layer stratified ocean and compared the theoretical prediction of his model with some of the observed features of Massachusetts Bay. Beardsley and Butman (1972) summarized the known data on Massachusetts Bay and concluded that many of the important questions, such as flushing time, could not be answered with the data then available.

The purpose of this work was to do detailed sections of the Bay to form a data base for future work and to use the data collected to determine the volume of fresh water in the Bay and compare the value so obtained with the outflow of the rivers. Many authors, such as Bigelow (1927), and Beardsley and Butman (1972), expressed belief that the Merrimac River, which lies outside Massachusetts Bay, accounts for most of the fresh water found in the Bay. However, this had never been determined volumetrically. By determining the correspondence between the volume of fresh water in the Bay and the river discharge this question could be resolved.

The study was conducted during the spring, since the vernal freshening of coastal bays is one of the major events that takes place there. Also, at this time the homogeneous state of the winter is eroded, and a thermocline and halocline are developed. Changes in salinity of the order of 3 $^{0}/00$ between the top and bottom layers are observed during the spring, and strong density gradients are formed.

From Bigelow's account of the vernal freshening, it was felt that in order to accurately report some of the effects taking place during the spring a complete survey of the Bay must be taken every two to three weeks.

There were five cruises: 29-30 March; 14-15 April and 21-22 April; 5-6 May; 2-3 June and 13-14 June. A timetable of cruises every two to three weeks could not be strictly adhered to due to equipment failure and bad weather. In fact, the second cruise had to be done in two parts, part one on 14-15 April and part two on 21-22 April because of equipment failure. The first cruise of 29-30 March and part two of the second cruise of 21-22 April were conducted on the Research Vessel W. E. Phipps, while all other cruises were done using the M.I.T. Research Vessel R. R. Shrock.

After studying the sections of Bigelow (1927), it was believed that a good picture of the spatial variations of the salinity and temperature in the Bay could be obtained by taking a vertical C.T.D. cast every 4-5 nautical miles (7-9 km).

In order to keep a fair amount of continuity from one cruise to another, an attempt was made to make vertical casts at the same positions as those of the first cruise. This was not always possible, however, because of the drift of the ship with currents and wind. The position of each cast is shown by the dots in Fig. 3.1 - 3.5. The position of the boat was determined by Loran B readings and radar fixes for the R. R. Shrock cruises, and by Loran C readings and radar fixes on the W. E. Phipps.

The fourth cruise of 2-3 June differed from the other cruises in that a small grid of vertical casts spaced 4 km apart was taken around two current meters located near the points labelled "C" in Fig. 3.4.

In Chapter 2 the instruments and their calibrations are discussed. The actual calibration curves are shown in Appendix B, Fig. 1 - 16. The salinity distribution on the surface and in the vertical profile is described in Chapter 3. The determination of the fresh water volume in the Bay, the description of the river flow, and the comparison of the river flow with the volume of fresh water in the Bay are presented in Chapter 4. Chapter 5 is a summary of the conclusions and a discussion of some of the work left to be done.

CHAPTER 2

INSTRUMENTATION

The instruments used for this study were a continuous recording C.T.D. built at M.I.T., used to obtain the vertical profile of salinity and temperature with depth, and a Bissett-Berman Model 6600 T Salinograph/Thermograph which produces a continuous record of surface salinity and temperature. To convert the parameters conductivity, temperature and pressure measured by the C.T.D. into salinity, a subroutine was obtained from the Woods Hole Oceanographic Institute (WHOI) (see Appendix A). The particular subroutine used is based on data from Cox, Culkin and Riley (1967).

The basic method for the conversion of conductivity into salinity, together with the subroutine used to do so, has been subject to question in recent years; see Wooster, Lee and Dietrich (1969), Fofonoff (1969), and Haidvogel (1972). The effect the answers to these questions will have on the absolute values of salinity presented in this report cannot be determined at this time.

To verify the calibrations of both the C.T.D. and the Salinograph, a surface sample was taken at each station of every cruise. In addition to these surface samples, some Nansen bottle casts were made to within 6m off the bottom at certain stations on the cruises of 5-6 May and 13-14 June, 1973. These bottle samples were then analysed at WHOI, on a laboratory salinometer accurate to ± .003 $^{0}/00$ in the range greater than 29.0 $^{0}/00$, and to ± .01 $^{0}/00$ in the range 27.0 - 29.0 $^{0}/00$.

For each cruise the following information was calculated from salinity readings of the various instruments: S_B, the salinity reading of the bottle; S_S, the salinity reading of the Salinograph; and S_{CTD}, the salinity reading of the C.T.D. The difference between the salinity reading of the C.T.D. and that of the bottle ($S_{CTD} - S_B$) was plotted against the station number, which in effect represents time since the stations were numbered sequentially from the start of each cruise (see Appendix B., Fig. 1-8). Similarly, the difference between the Salinograph reading and the bottle reading ($S_S - S_B$) was plotted against the station number (see Appendix B, Fig. 9-13).

The mean and standard deviations of these differences were calculated and the results are shown in Table 2.1 for C.T.D. and Table 2.2 for Salinograph. The following formulas were used in the computations of the mean and standard deviations for each instrument. Let $x_i = (S_I - S_B)_i$ where I represents the particular instrument, C.T.D. or Salinograph, and i is the station number. Then $\bar{x}$, the mean deviation, is given by

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

where N is the total number of stations.

The standard deviation, δ, is given by

$$\delta = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N - 1}}$$

TABLE 2.1

MEAN DEVIATIONS OF THE DIFFERENCE BETWEEN C.T.D. AND BOTTLE READINGS

Date	$\bar{x}$	δ	M.S.T.
29-30 March	.27	.028	3.3
14-15 April	.28	.026	4.0
21-22 April	.32	.026	5.9
5-6 May	.35	.040	8.5
5-6 May (bottom samples)	.32	.038	4.2
2-3 June	.45	.052	12.6
13-14 June	.54	.044	16.2
13-14 June (bottom samples)	.37	.033	4.5

$\bar{x}$ ≡ Mean Deviation ($^0/00$)

δ ≡ Standard Deviation ($^0/00$)

M.S.T. ≡ Mean in situ Temperature, (°C)

TABLE 2.2

MEAN DEVIATIONS OF THE DIFFERENCE BETWEEN
SALINOGRAPH AND BOTTLE READINGS

Date	$\bar{x}$	δ	M.S.T.
29-30 March	.12	.009	3.3
14-15 April	.12	.024	4.0
21-22 April	.10	.028	5.9
5-6 May	.16	.042	8.5
13-14 June	.18	.044	16.2

$\bar{x}$ ≡ Mean Deviation ($^0/00$)

δ ≡ Standard Deviation ($^0/00$)

M.S.T. ≡ Mean in situ Temperature, (°C)

It was found that the mean deviation of the difference between the C.T.D. reading and the bottle reading increased as the spring progressed. This may have been due either to temperature, since the surface waters were becoming warmer with each cruise, or it may have been some drift of the calibration of the instrument with time. To settle this dilemma the deviations for each sample were plotted against their in situ temperature for two cruises. For the bottles of the cruise 29-30 March and for those of the cruise 5-6 May these plots showed what seemed to be a random variation with in situ temperature (see Appendix B, Fig. 14-15).

On the other hand, it was realized that the change in mean deviation of the C.T.D. readings from the bottle readings as the survey progressed was not a drift of the calibration with time, since the mean deviations of the samples from the bottom did not correspond with the mean deviations of the samples from the surface. This is shown in Table 2.1, for the cruises of 5-6 May and 13-14 June. The mean deviations for each set of samples from the surface, together with the mean deviations of each group of bottom samples, were then plotted against their mean in situ temperature (M.S.T.). There seemed to be a fair correspondence between the mean deviations of the samples with their mean in situ temperature (see Appendix B, Fig. 16). Therefore, this curve of mean deviations versus mean in situ temperature was used to correct the values of salinity obtained from the C.T.D.

The mean deviation of the difference of the Salinograph readings from the bottle readings was used to correct the salinity readings from the Salinograph (see Table 2.2).

CHAPTER 3

SALINITY DISTRIBUTION

3.A. Surface Distribution

By the time of the first cruise, March 29-30, the effect of spring run-off was already felt in Massachusetts Bay. This was an unusually early time of the year for the spring run-off, since on March 24, 1920 no vernal freshening was observed even at the innermost stations off Massachusetts (Bigelow, 1927). This year, however, water from the Merrimac had already reached the latitude of the lightship (Fig. 3.1) which is 53.8 km south of the mouth of the river.

At this time the water from the rivers north of Cape Ann occupied the easternmost part of Massachusetts Bay, while the water from the rivers that emptied directly into the Bay was at the westernmost part (Fig. 3.1). This left a pool of relatively high salinity water in the middle of the Bay, the center of the pool being at about 42°..24'..24" N and 070°..25'..42" W, i.e., near #17 as marked in Fig. 3.1.

Bigelow (1927) reported that the freshening of the water in Massachusetts Bay varies considerably from year to year, since it depends greatly to what extent the river run-off from north of Cape Ann hugs the coast line. This was clearly observed by the time of the second cruise, 21-22 April (Fig. 3.2). It was observed that the tongue of fresh water from north of Cape Ann had moved approximately five nautical miles, 9.3 km, to the west and was now inside Stellwagen Bank.

No new low of salinity was observed at this time, but the pool of 31.0 - 31.6 $^{0}/00$ water that had been in the middle of the Bay three weeks earlier had now disappeared and the 30.4 $^{0}/00$ contour had moved further out from the coastline, evidence that a significant amount of freshening had taken place.

It was still easy to differentiate the water from the rivers north of Cape Ann (Merrimac, Parker, Ipswich) from those that empty directly into the Bay (Charles, Mystic, Neponset, Mother Brook), by the rise and fall in salinity from west to east (see Fig. 3.2).

By 5-6 May, the full effect of the spring run-off was observed (Fig. 3.3). The low salinity tongue originating north of Cape Ann had moved a further five nautical miles, 9.3 km, westward, and its salinity had dropped by 2.6 $^{0}/00$ from 30.6 $^{0}/00$ to 28.0 $^{0}/00$. The fresh water was observed much further south than before and may even have been as far south as the Cape Cod Canal (Fig. 4.1), although no data was collected to verify this.

The first two weeks of May generally mark the end of the freshening of the surface waters, (Bigelow, 1927), and in that respect this year seems to follow previous years. However, there was considerably more fresh water run-off this year than in previous years. Bigelow (1927) reports that the surface salinity on May 4, 1920, was 29.1 $^{0}/00$ and was close to the minimum for the year. This year, 1973, the salinity on May 5-6 was as low as 28.0 $^{0}/00$ over a major portion of the Bay.

Also, at this time the region close to the shore of the Bay which was marked by the 30.4 $^0/00$ isohaline of 21-22 April (Fig. 3.2), was now marked by the 30.0 $^0/00$ isohaline (Fig. 3.3). The fact that the middle of the Bay, which is freshened by the Merrimac, etc., is 2 $^0/00$ less saline than the waters near the coastline, freshened by the Charles, etc., indicates how much more the freshening in Massachusetts Bay depends on the rivers north of Cape Ann rather than those that empty into the Bay directly.

Following the same trend as was observed by Bigelow (1927) the Bay began to "salt up" soon after this date. By 2-3 June the low salinity tongue of 28.0 $^0/00$ water in the middle of the Bay had increased to about 28.8 $^0/00$, with only a small tongue of 28.6 $^0/00$ extending to the tip of Stellwagen Bank (see Fig. 3.4).

On the other hand, the water nearest the coastline showed further decrease and there was no 30.0 $^0/00$ water in the Bay at this time. This, however, does not necessarily mean that the Charles, Neponset and Mystic have continued discharging at a relatively high rate while the Merrimac and others north of Cape Ann have started to diminish in their outflow. It could be due to the Merrimac's water from the middle of the Bay having had time to diffuse horizontally and thus lower the salinity of the water as we go west from the middle of the Bay. Which of these two factors is the more important will be considered later, when the report compares the river outflow for the corresponding months.

By 13-14 June, the salting effect was being felt all over the Bay, thus marking the end of the spring run-off. The lowest salinity water is still in the middle of the Bay with the salinity increasing to both the east and the west (Fig. 3.5). At this time pockets of high salinity water among the low salinity water are observed; this feature is not unique to Massachusetts Bay but seems to be a characteristic of the rest of the Gulf of Maine (Bigelow, 1927).

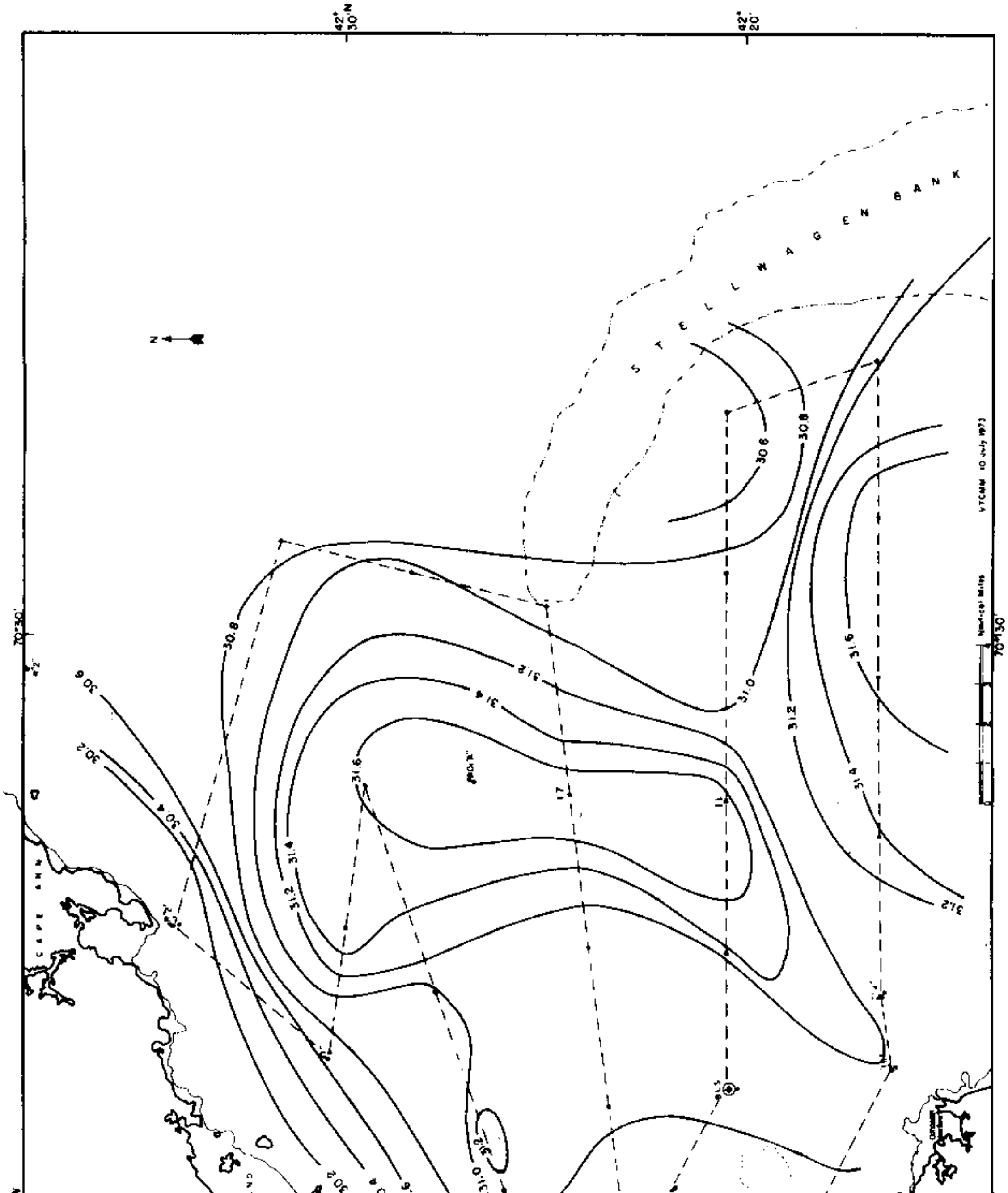
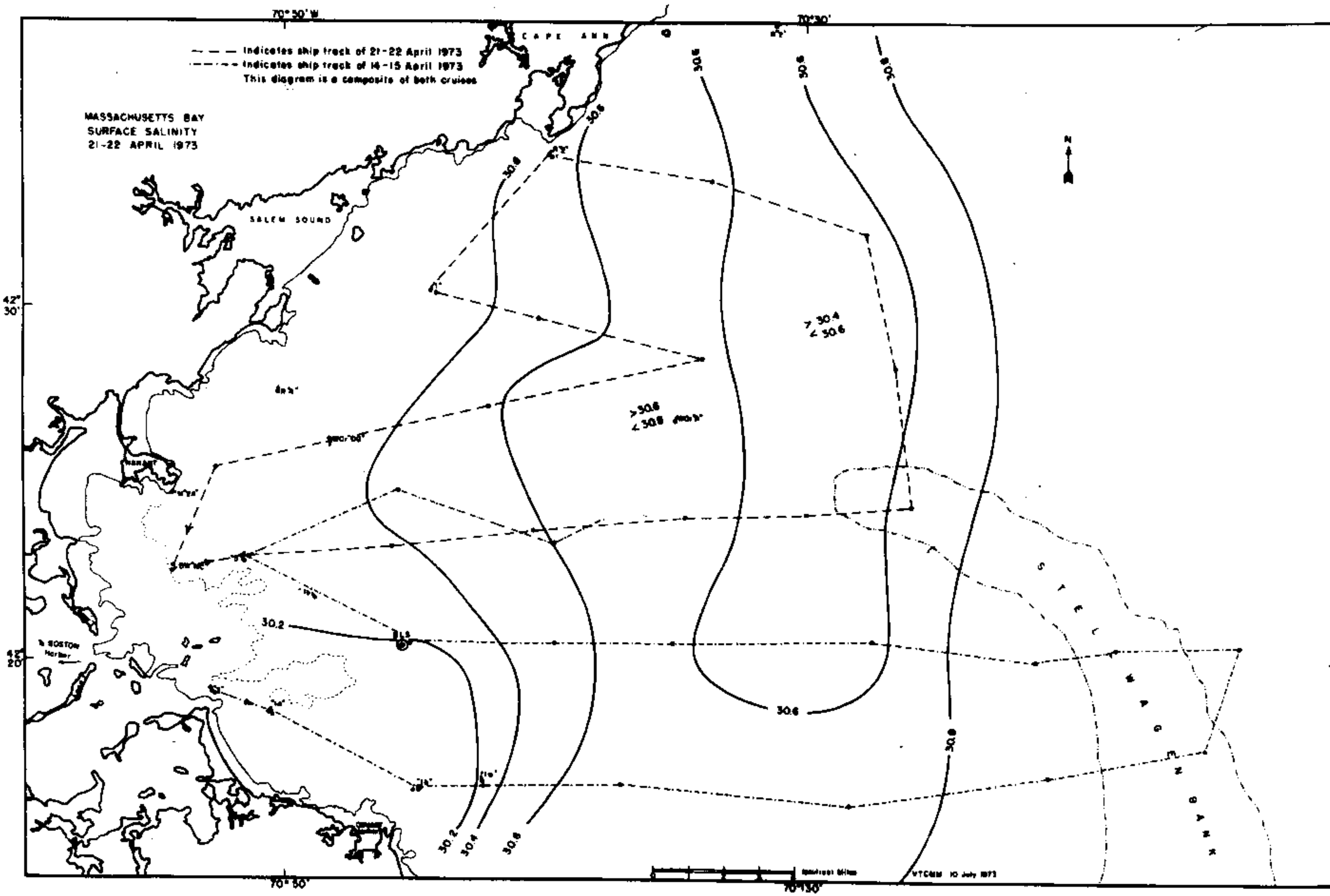

MASSACHUSETTS BAY
SURFACE SALINITY
29-30 MARCH 1973
---- indicates ship track
STELLWAGEN BANK
CAPE ANN
SALEM SOUND
BOSTON Harbor
42° 30' N
42° 20'
70° 50' W
70° 30'
30.2
30.4
30.6
30.8
31.0
31.2
31.4
31.6

Figure 3.1



MASSACHUSETTS BAY
SURFACE SALINITY
21-22 APRIL 1973
Indicates ship track of 21-22 April 1973
Indicates ship track of 14-15 April 1973
This diagram is a composite of both cruises
CAPE ANN
SALEM SOUND
STELLWAGEN BANK
Boston Harbor
70°50' W
70°30'
70°50'
42° 30'
42° 30' N
42° 20'
> 30.4
< 30.6
> 30.6
< 30.8
30.2
30.4
30.6
30.8
N

Figure 3.2

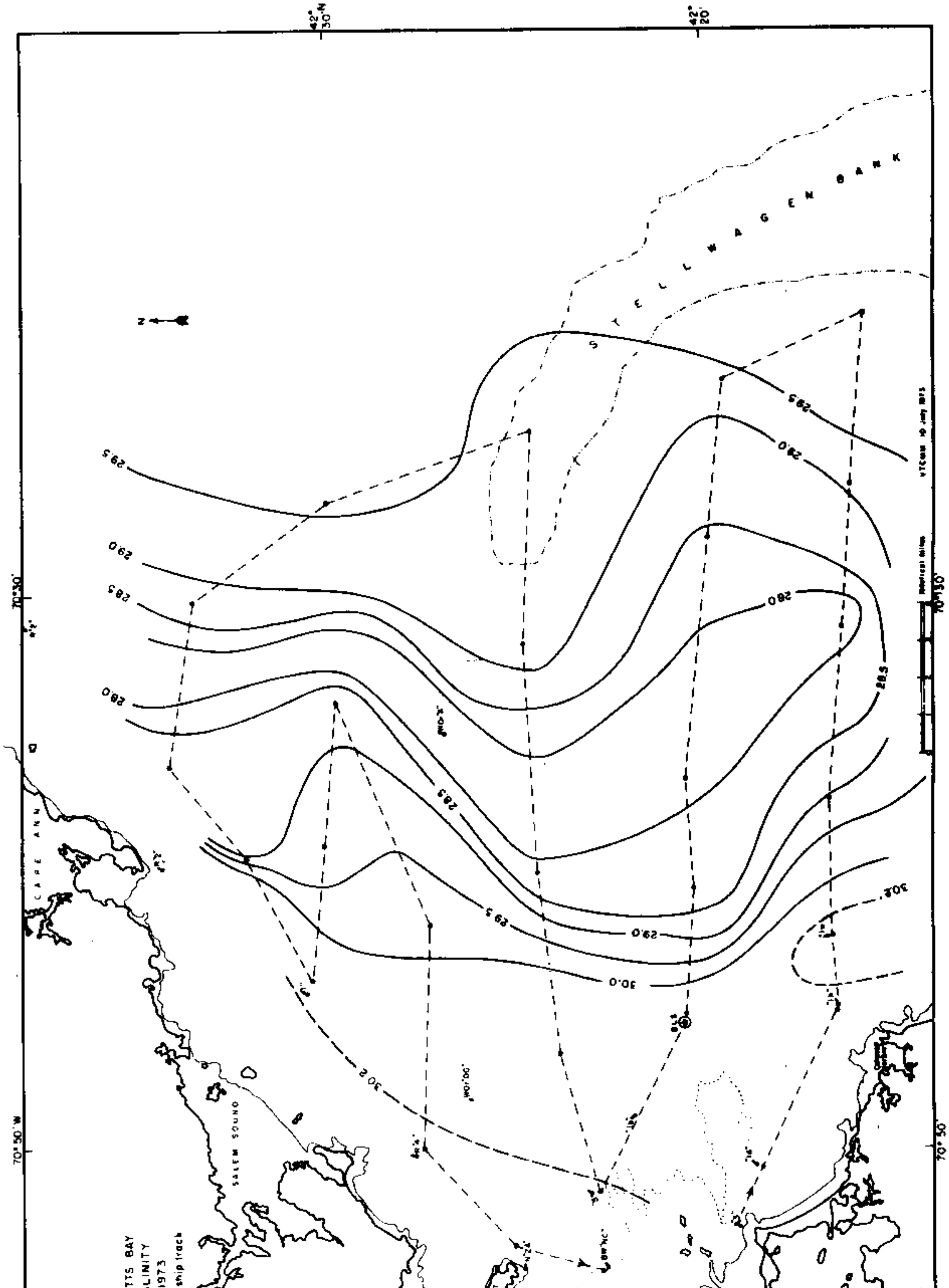

MASSACHUSETTS BAY
SURFACE SALINITY
5-6 MAY 1973
--- Indicates ship track
STELLWAGEN BANK
CAPE ANN
SALEM SOUND
BOSTON Harbor
42° 30' N
42° 20'
70° 50' W
70° 30'
28.0
28.5
29.0
29.5
30.0

Figure 3.3

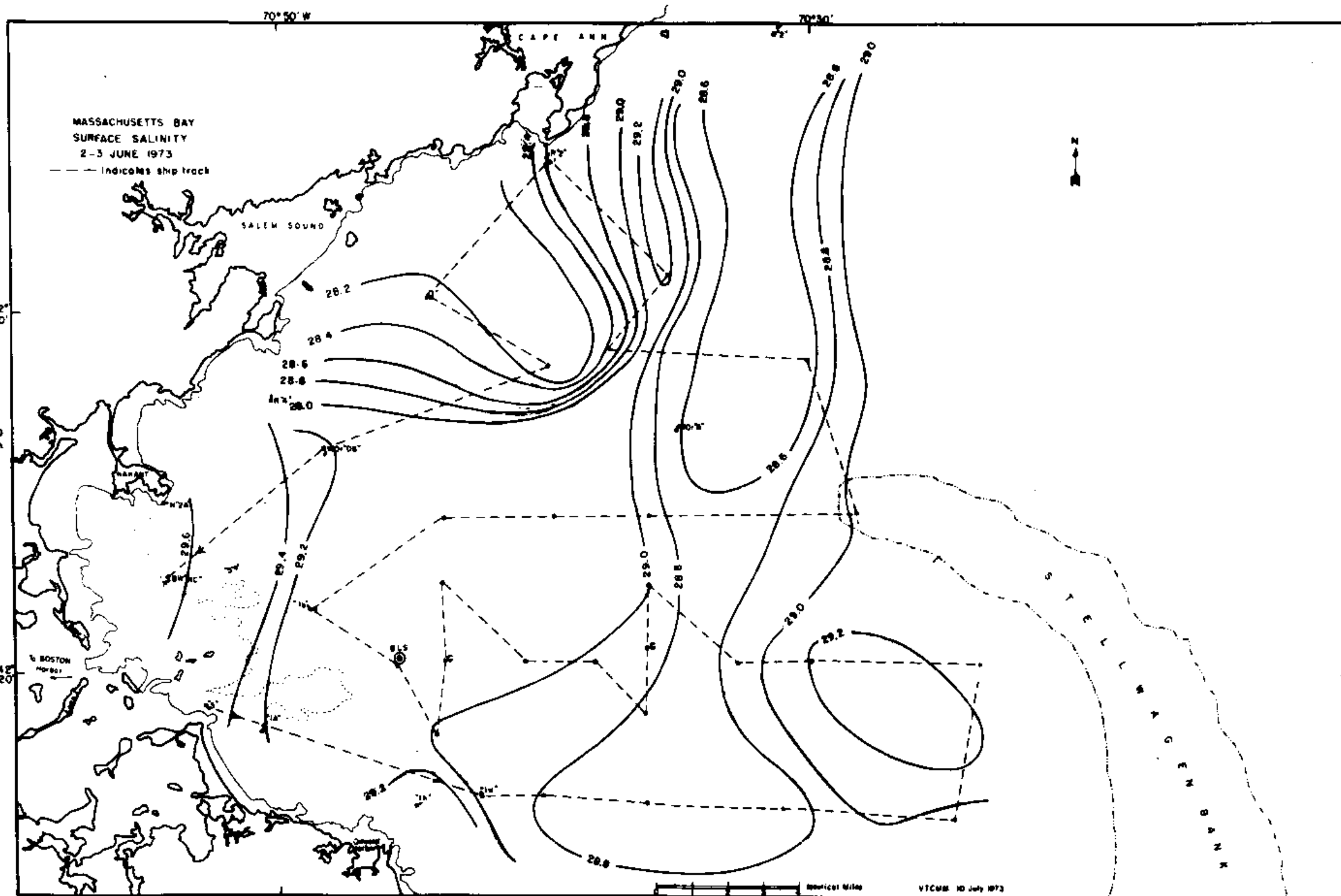

MASSACHUSETTS BAY
SURFACE SALINITY
2-3 JUNE 1973
— — — Indicates ship track
CAPE ANN
SALEM SOUND
STELLWAGEN BANK
BOSTON Harbor
70°50' W
70°30'
42° 30' N
42° 20'
28.2
28.4
28.6
28.8
29.0
29.2
29.4
29.6
Nautical Miles
VTCMM 10 July 1973

Figure 3.4

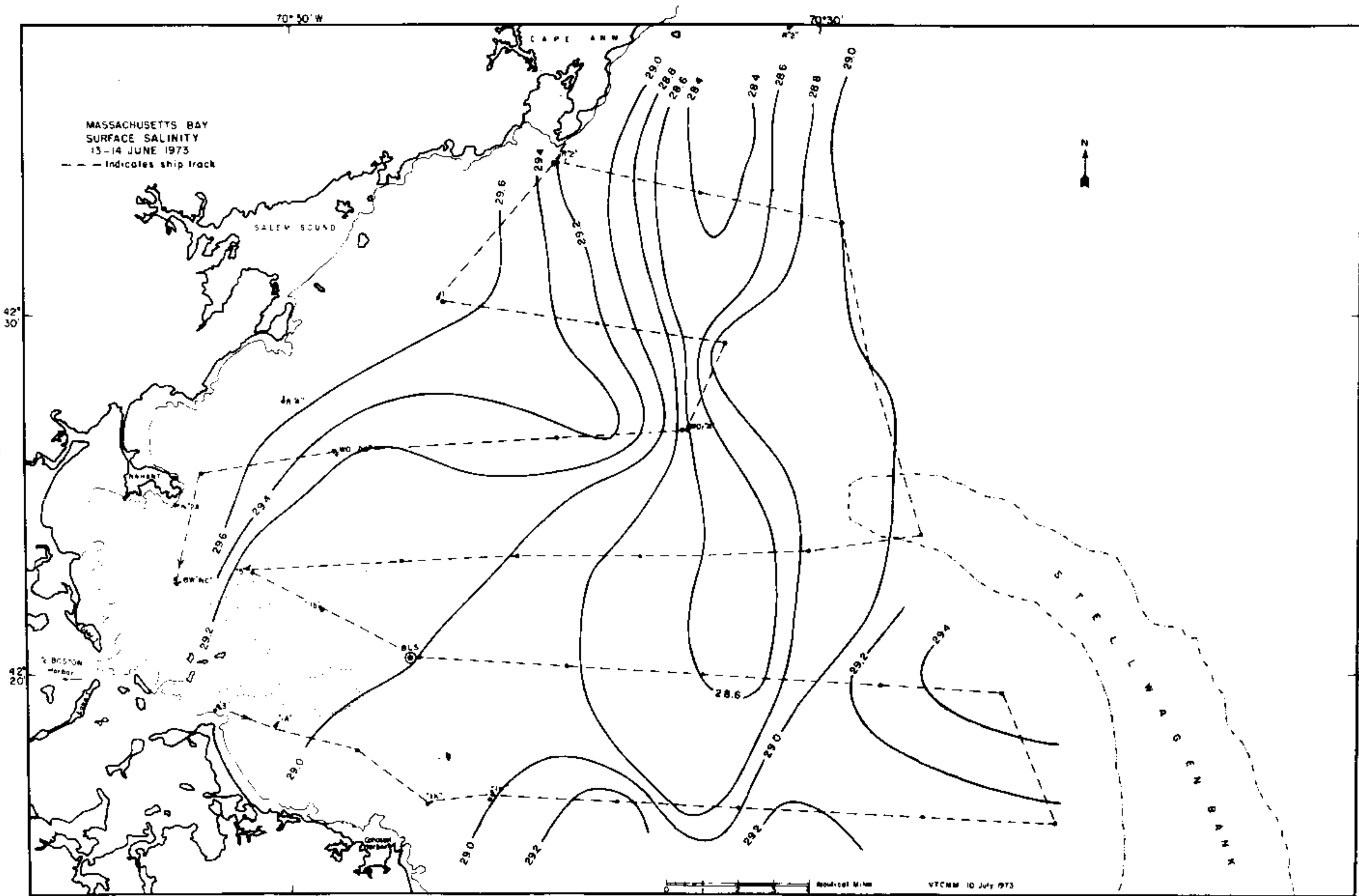

MASSACHUSETTS BAY
SURFACE SALINITY
13-14 JUNE 1973
— — — Indicates ship track
70° 50' W
70°30'
42° 30' N
42° 20'
CAPE ANN
SALEM SOUND
BOSTON Harbor
STELLWAGEN BANK
N
BLS
29.0
28.8
28.6
28.4
29.6
29.4
29.2
Nautical Miles
VTCMM 10 July 1973

Figure 3.5

3.B. Vertical Distribution

The effect of the spring run-off in the vertical profile is seen to be quite deep even as early as 29-30 March. In Section A, Fig. 3.6, the freshening due to the Merrimac, Parker and Ipswich Rivers is observed as a small bowl of low salinity water at station 9, but with its influence being felt almost to station 11 about 18 km to the West, and to a depth of 25m in the region of station 10.

The waters from the Charles, Neponset and Mystic are seen in Fig. 3.6 in the upper left hand corner as a much smaller freshening with lower salinity than the bottom water but almost 1 $^0/00$ higher than that of the Merrimac. These two masses of fresh water are separated by a small ridge of high salinity water, left over from winter, centered about station 11.

The Merrimac's water is not fully observed in Section B of the 29-30 March (Fig. 3.7) since this section was drawn just to the west of the flow of the Merrimac (Fig. 3.1). However, the freshening around the coastline is easily observible and the 31.4 $^0/00$ isohaline is 25m deep at station 22.

By 14-15 April the Merrimac's water is observed as a bowl of 30.6 $^0/00$ water centered at station 13, (Fig. 3.9) with a depth of about 25m. The fact that this low salinity water is observed so far south and so deep is evidence of the fresh water volume of the rivers north of Cape Ann and also of the mixing in the water column.

Once more the water of the Merrimac is separated from the Charles etc., by a ridge of high salinity water. However, by this time, 14-15 April, the ridge had dropped in salinity from approximately 31.8 $^{0}/00$ at the surface to approximately 30.8 $^{0}/00$ at the surface.

The Merrimac water is again evident to about 20m, at Section B, 15 km to the north of Section A (Fig. 3.10) on 21-22 April. The near-shore water shows up much more strongly in this section than in the previous ones, and is probably due to the cumulative effect of the spring run-off.

By 5-6 May, the full effect of the vernal freshening is being felt in the Bay. At Section A, (Fig. 3.12) there is a small bowl of 28.0 $^{0}/00$ water encompassing stations 11 and 12; this water represents almost the lowest salinity water the Bay would contain for this spring. At this time, the halocline layer is well developed and is between 5-10m. This contrasts decidedly with Fig. 3.9, Section A, 14-15 April, in which no halocline is observed.

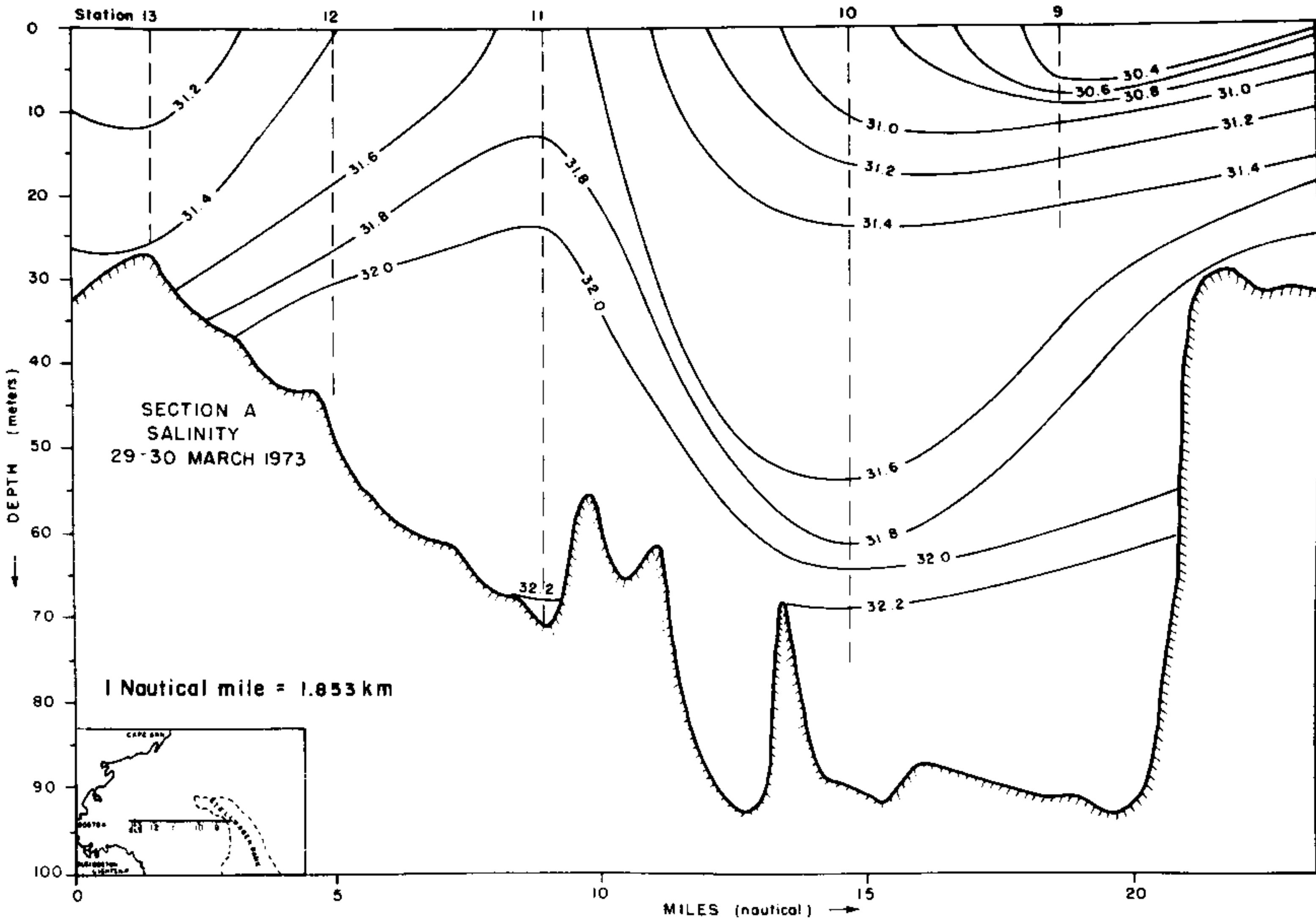
Section B, 5-6 May (Fig. 3.13), shows the same general characteristics as described for Section A, 5-6 May. A good indication of how much freshening had taken place in the two weeks between the cruises of 21-22 April and that of 5-6 May is given by the 30.6 $^{0}/00$ isohaline. In Fig. 3.10 for 21-22 April, the 30.6 $^{0}/00$ isohaline is only shown as a small intrusion from the west with a maximum depth of 7m. In Fig. 3.13 for 5-6 May, on the other hand, the 30.6 $^{0}/00$ isohaline stretches across the whole Bay at an average depth of 12m.

At the time of the next cruise, 2-3 June, the surface waters have started to get more saline. However, the bottom waters are still getting fresher, which corresponds with the observation of Bigelow (1927) that the bottom waters reach their lowest salinity after the surface waters have started to get more saline. A comparison of Figures 3.12 and 3.15, Sections A for 5-6 May and 2-3 June respectively, shows that while there are still regions of 32.2 $^0/00$ water near the bottom at 5-6 May, there are none on 2-3 June. Also, by 2-3 June the 32.0 $^0/00$ isohaline has dropped by about 10m.

Similar effects are observed at Section B, 2-3 June (Fig. 3.16). In this case, though, not only has the 32.2 $^0/00$ water disappeared but the most saline water is 31.8 $^0/00$. The halocline layer is easily observed at between 7-15m at the eastern side of the Bay.

By the last cruise of 13-14 June, the surface layer had not become appreciably more saline than that of 2-3 June. However, at Section A (Fig. 3.18), the bottom waters seemed to have gotten more saline. This is seen by the 32.0 $^0/00$ isohaline having moved about 5m upward.

At Section B (Fig. 3.19), however, the bottom waters continued to become fresher and the 31.8 $^0/00$ isohaline had moved downward by approximately 20m in the 11 days between the last two cruises. This difference between Section A and Section B is not strange since Section B is located closer to the rivers that contribute the most to the vernal freshening. This would mean that Section B would experience the vernal freshening sooner than Section A and the salting of the Bay later than Section A.


Station 13
12
11
10
9
SECTION A
SALINITY
29-30 MARCH 1973
1 Nautical mile = 1.853 km
DEPTH (meters)
MILES (nautical)
30.4
30.6
30.8
31.0
31.2
31.4
31.6
31.8
32.0
32.2
Figure 3.6

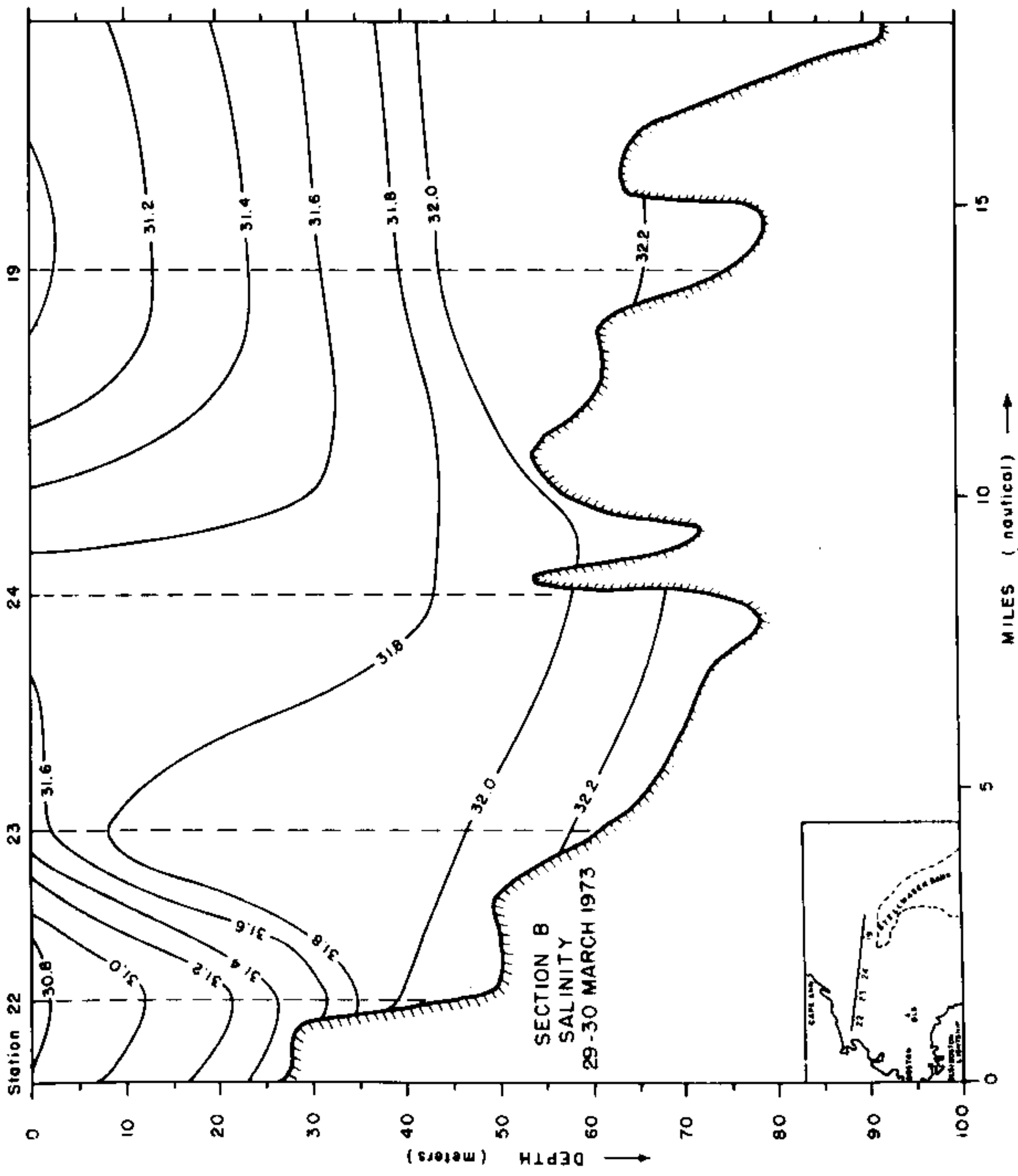
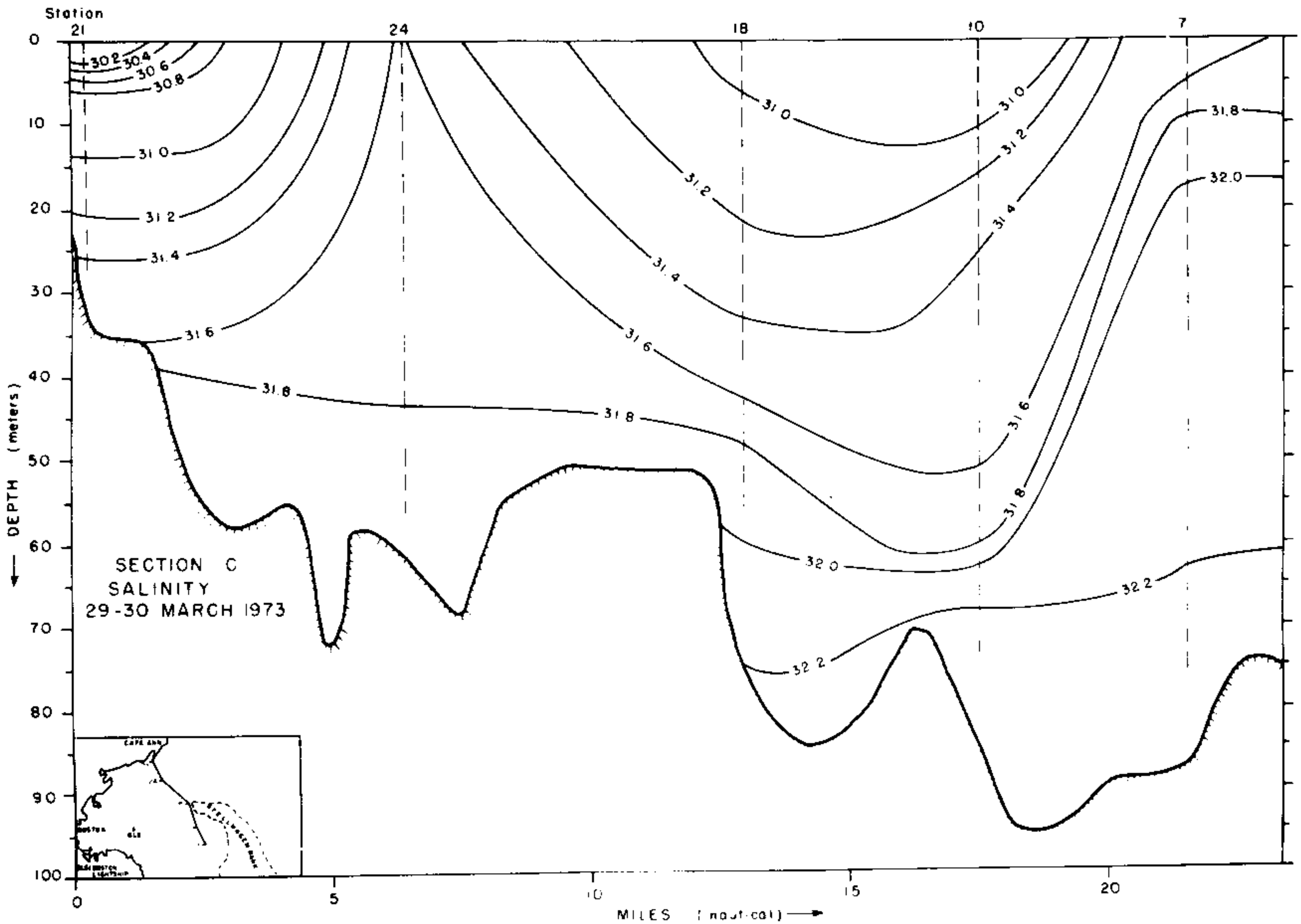

Station 22
23
24
19
DEPTH (meters)
MILES (nautical)
SECTION B
SALINITY
29-30 MARCH 1973
30.8
31.0
31.2
31.4
31.6
31.8
32.0
32.2

Figure 3.7



Station
21
24
18
10
7
SECTION C
SALINITY
29-30 MARCH 1973
DEPTH (meters)
MILES (naut·cal)

Figure 3.8

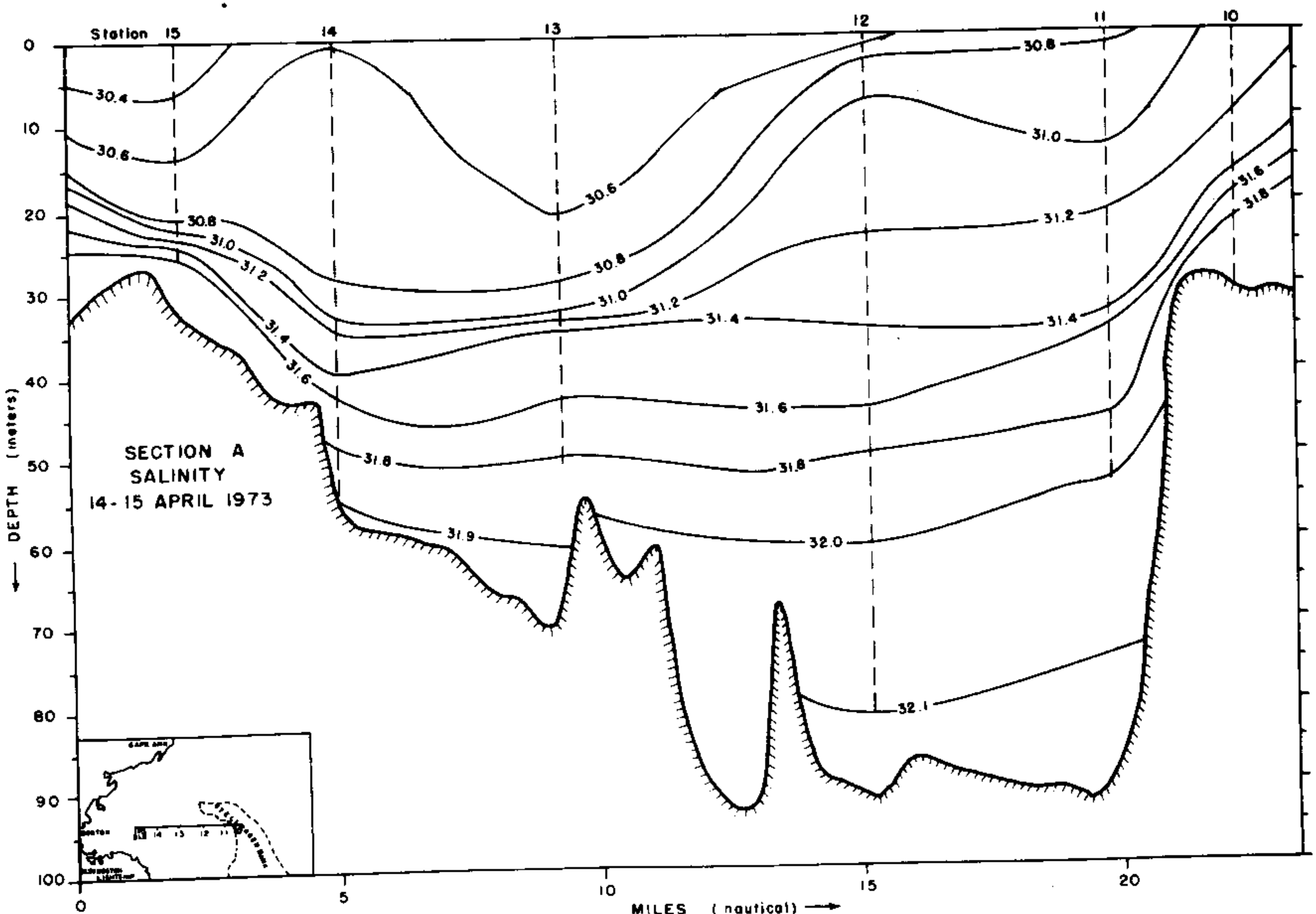
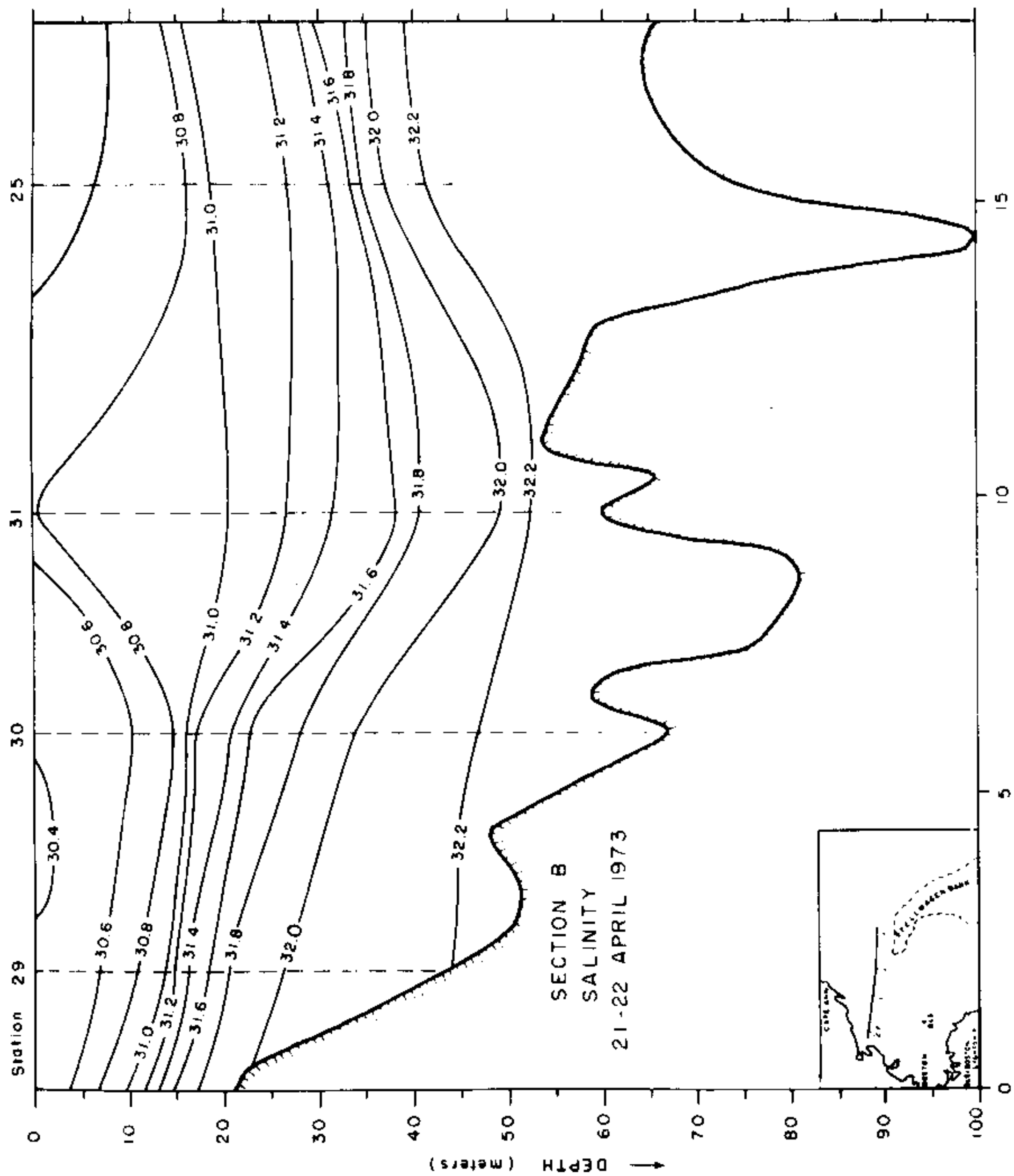

Station 15 14 13 12 11 10
SECTION A
SALINITY
14-15 APRIL 1973
30.4
30.6
30.8
31.0
31.2
31.4
31.6
31.8
31.9
32.0
32.1
DEPTH (meters)
MILES (nautical)
0 10 20 30 40 50 60 70 80 90 100
0 5 10 15 20

Figure 3.9



Station 29
30
31
25
SECTION B
SALINITY
21-22 APRIL 1973
DEPTH (meters)
MILES (nautical)

Figure 3.10

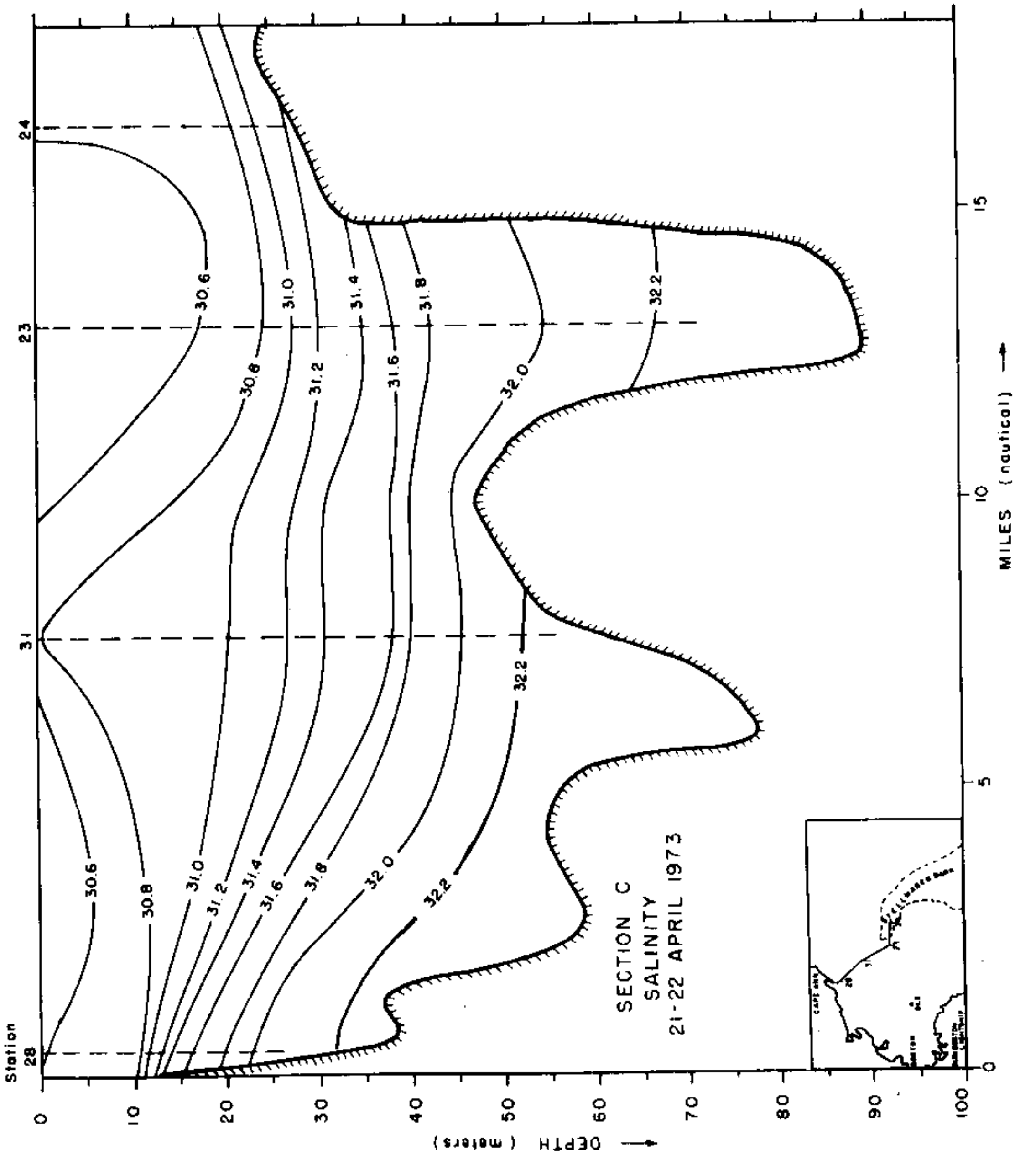
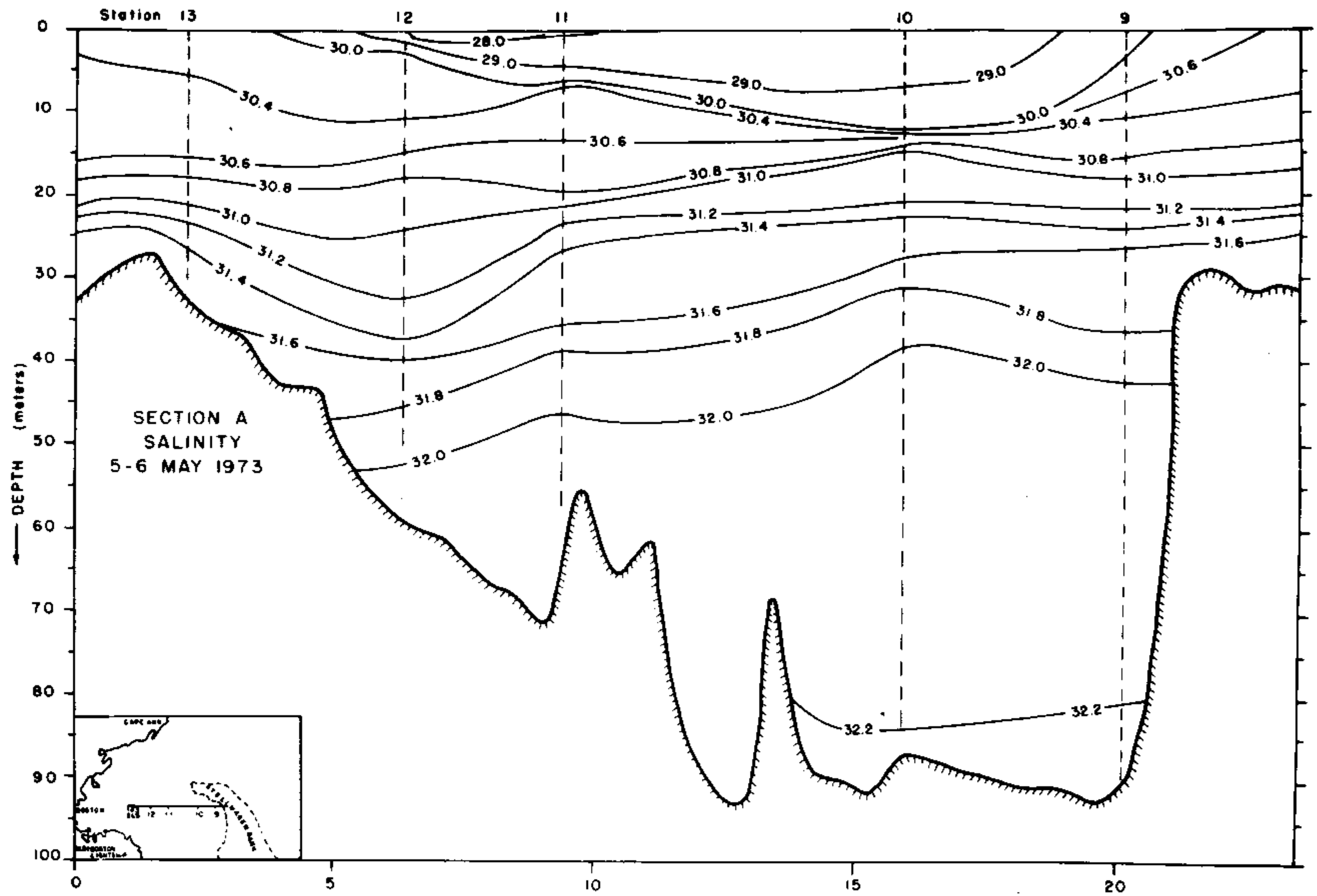

SECTION C
SALINITY
21-22 APRIL 1973
Station
28
31
23
24
30.6
30.8
31.0
31.2
31.4
31.6
31.8
32.0
32.2
DEPTH (meters)
MILES (nautical)
0
5
10
15
0
10
20
30
40
50
60
70
80
90
100

Figure 3.11



SECTION A
SALINITY
5-6 MAY 1973
Station 13
12
11
10
9
DEPTH (meters)
MILES (nautical)

Figure 3.12

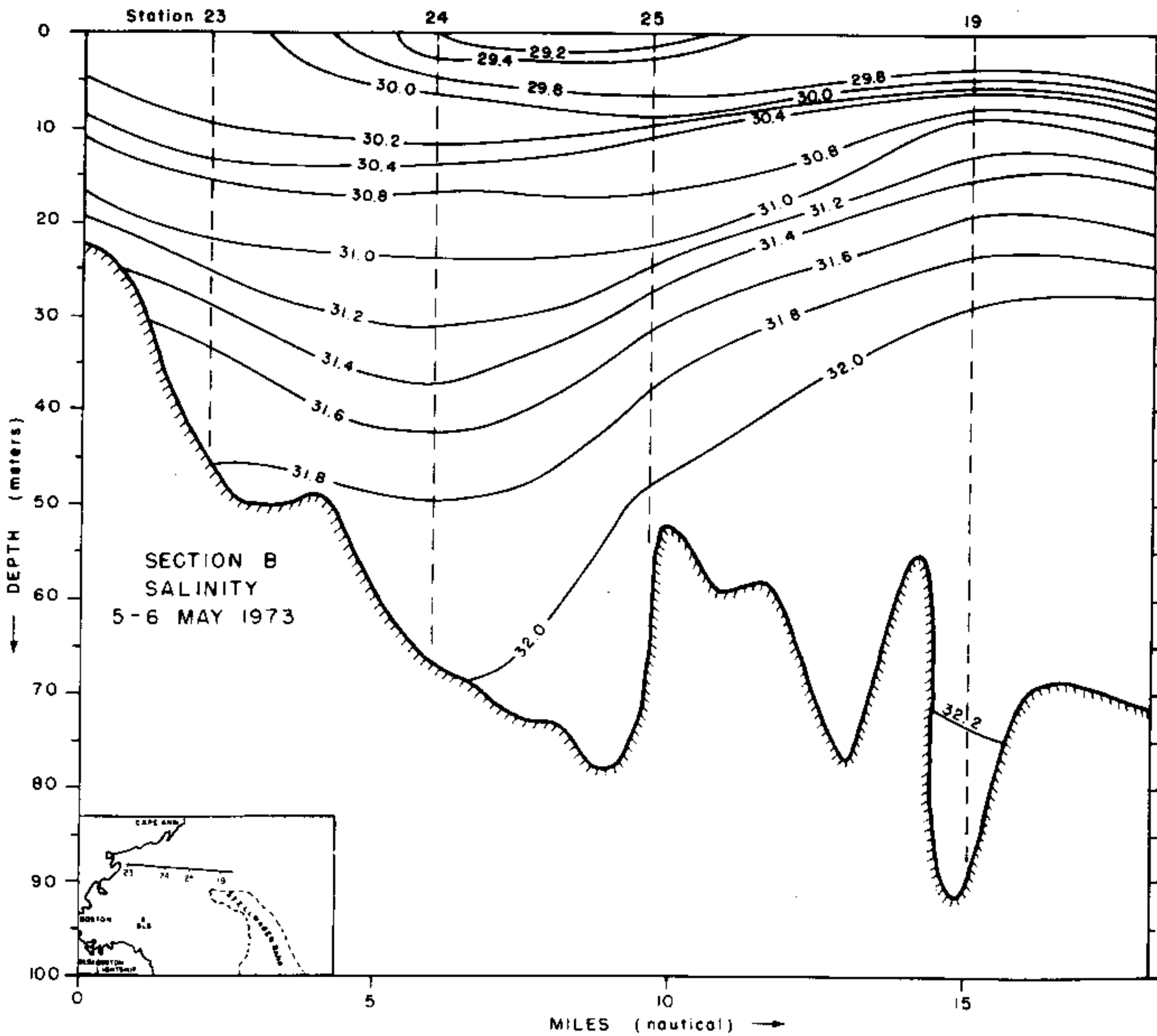

Station 23
24
25
19
SECTION B
SALINITY
5-6 MAY 1973
DEPTH (meters)
MILES (nautical)
29.2
29.4
29.8
30.0
30.2
30.4
30.8
31.0
31.2
31.4
31.6
31.8
32.0
32.2
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15

Figure 3.13

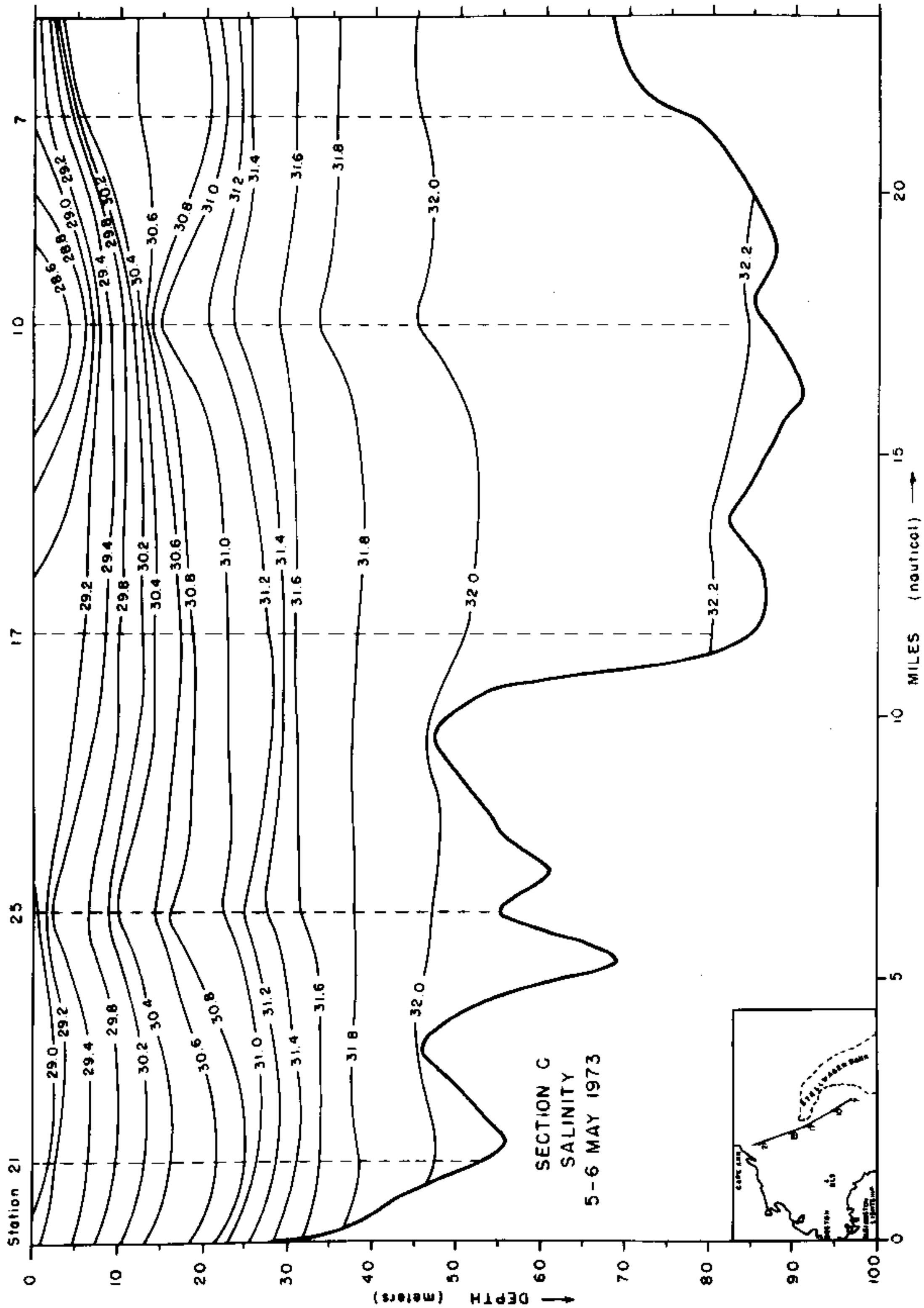

Station 21
25
17
10
7
SECTION C
SALINITY
5-6 MAY 1973
DEPTH (meters)
MILES (nautical)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
29.0
29.2
29.4
29.8
30.2
30.4
30.6
30.8
31.0
31.2
31.4
31.6
31.8
32.0
32.2
28.6
28.8

Figure 3.14

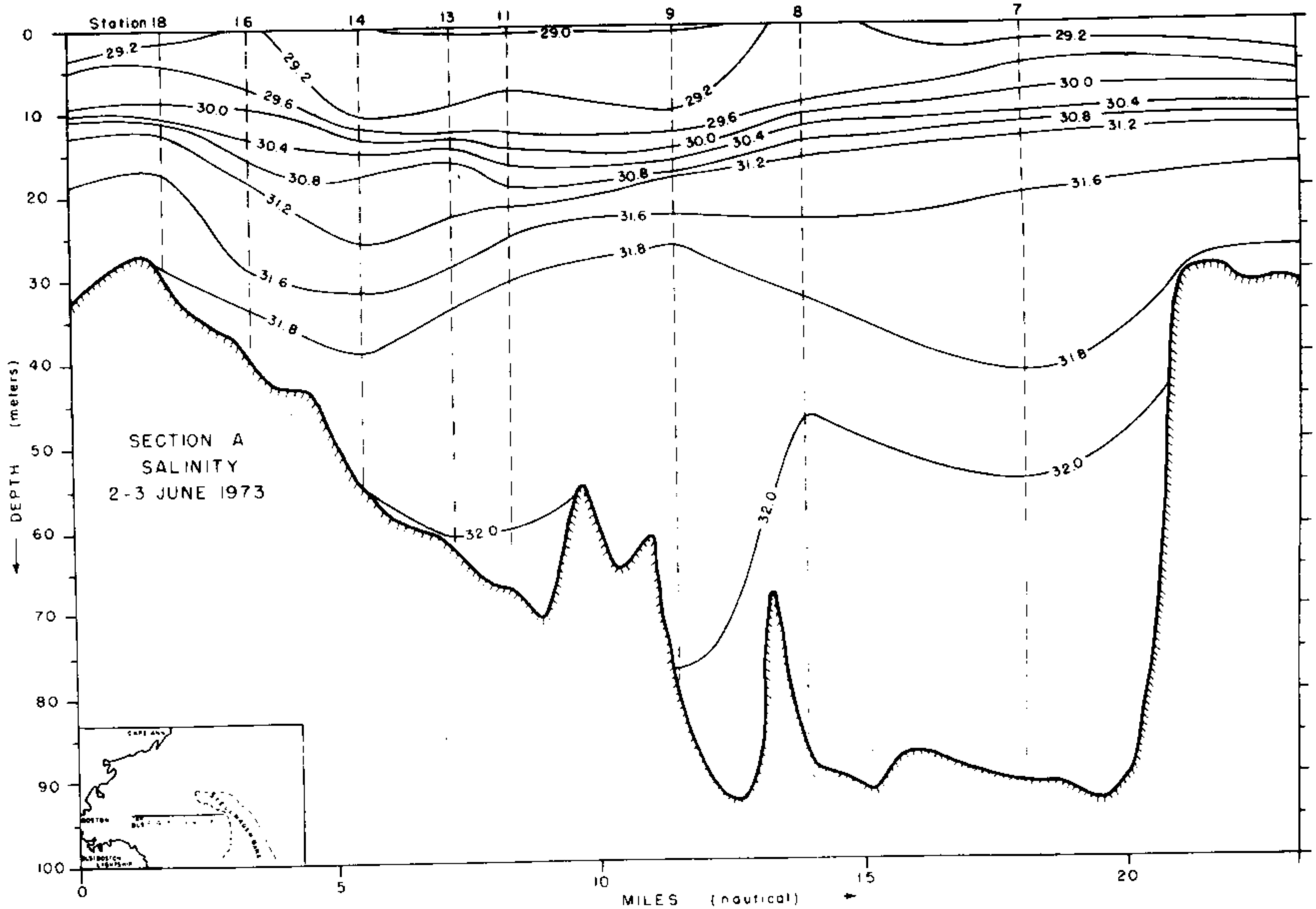
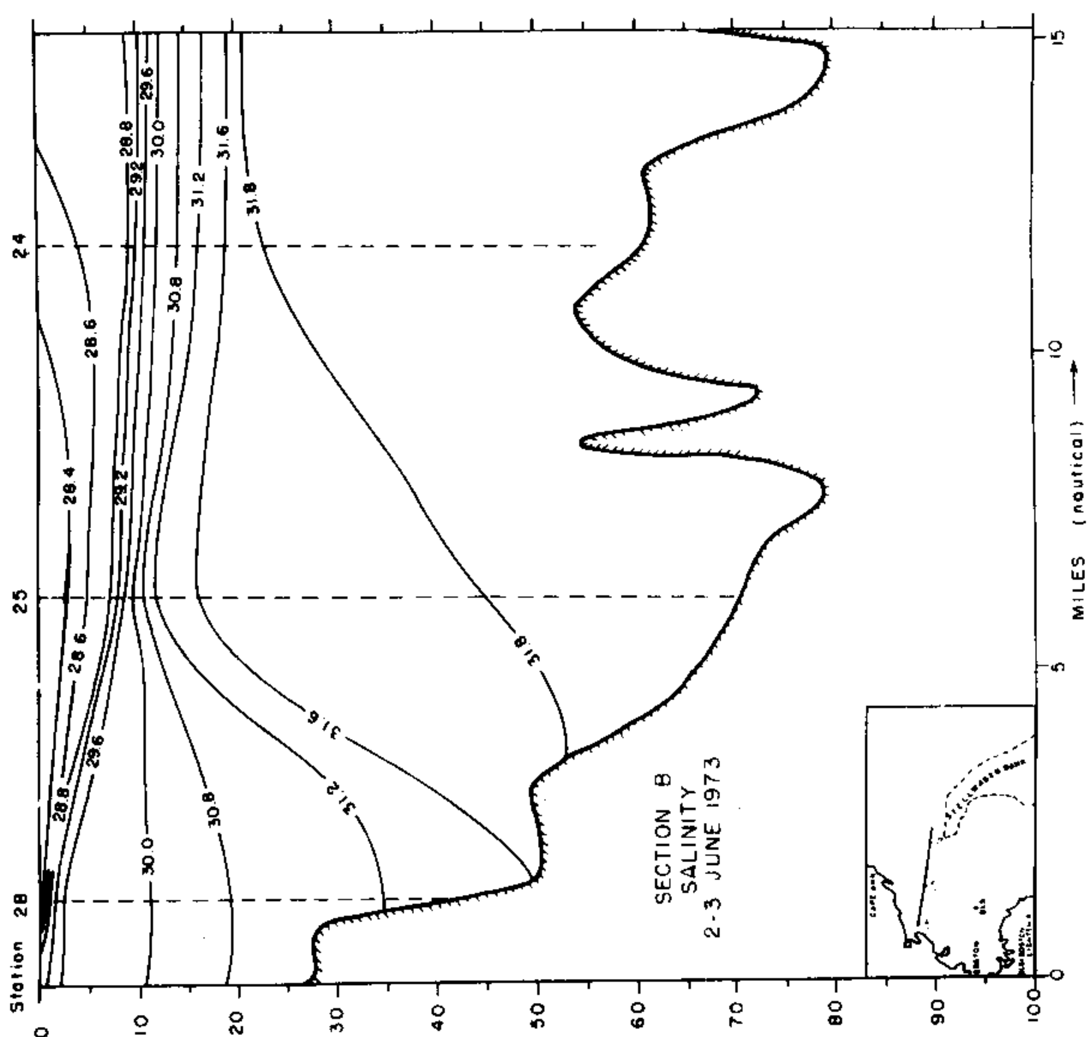

Station 18
16
14
13
11
9
8
7
SECTION A
SALINITY
2-3 JUNE 1973
DEPTH (meters)
MILES (nautical)
29.0
29.2
29.6
30.0
30.4
30.8
31.2
31.6
31.8
32.0

Figure 3.15


Station
28
25
24
SECTION B
SALINITY
2-3 JUNE 1973
DEPTH (meters)
MILES (nautical)
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28.8
29.2
29.6
30.0
30.8
31.2
31.6
31.8

Figure 3.16

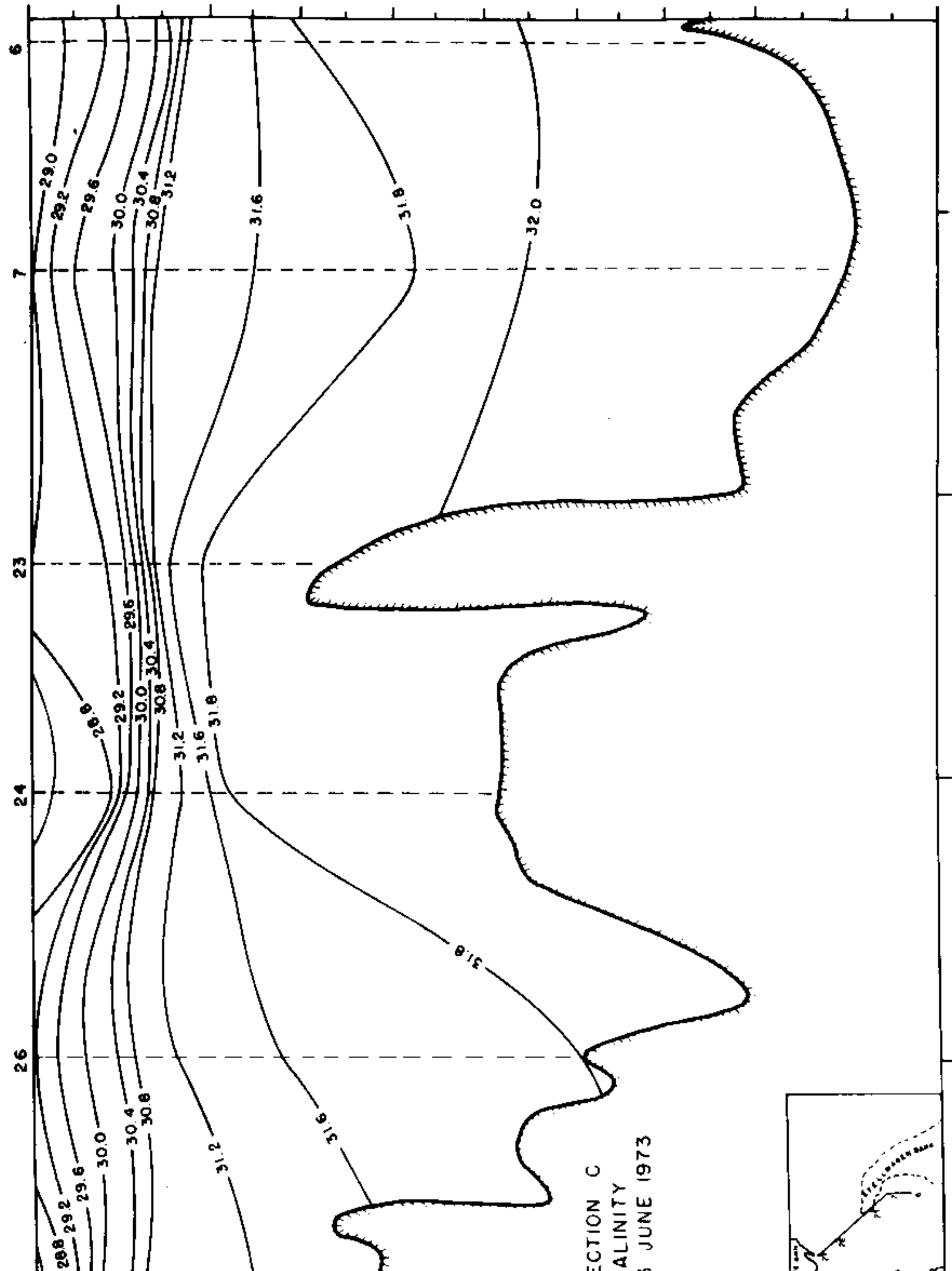
SECTION C
SALINITY
2-3 JUNE 1973
Station
27
26
24
23
7
6
DEPTH (meters)
MILES (nautical)
28.8
29.0
29.2
29.6
30.0
30.4
30.8
31.2
31.6
31.8
32.0

Figure 3.17

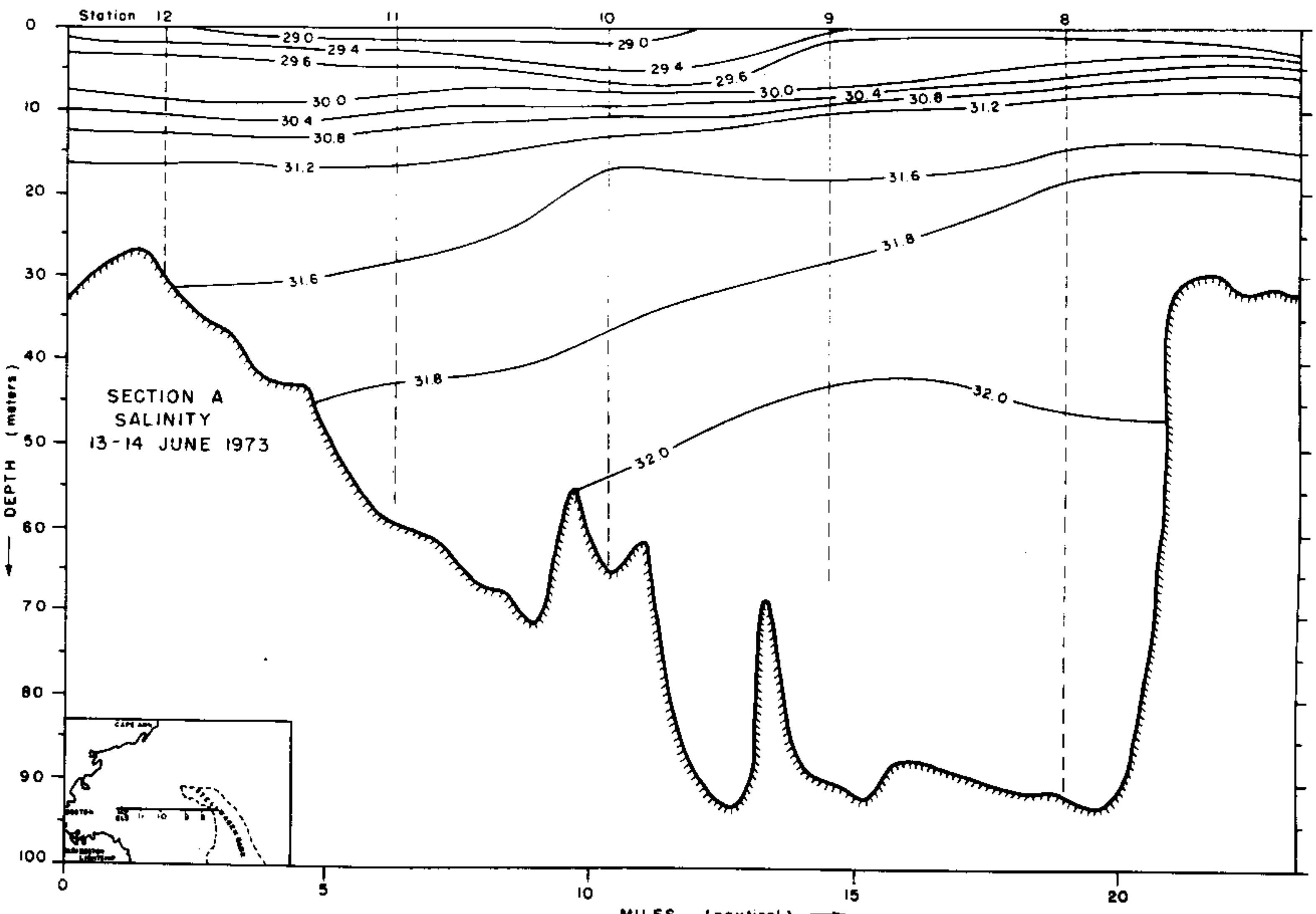
Station 12
11
10
9
8
29.0
29.4
29.6
30.0
30.4
30.8
31.2
31.6
31.8
32.0
SECTION A
SALINITY
13-14 JUNE 1973
DEPTH (meters)
MILES (nautical)
0
10
20
30
40
50
60
70
80
90
100
5
15

Figure 3.18

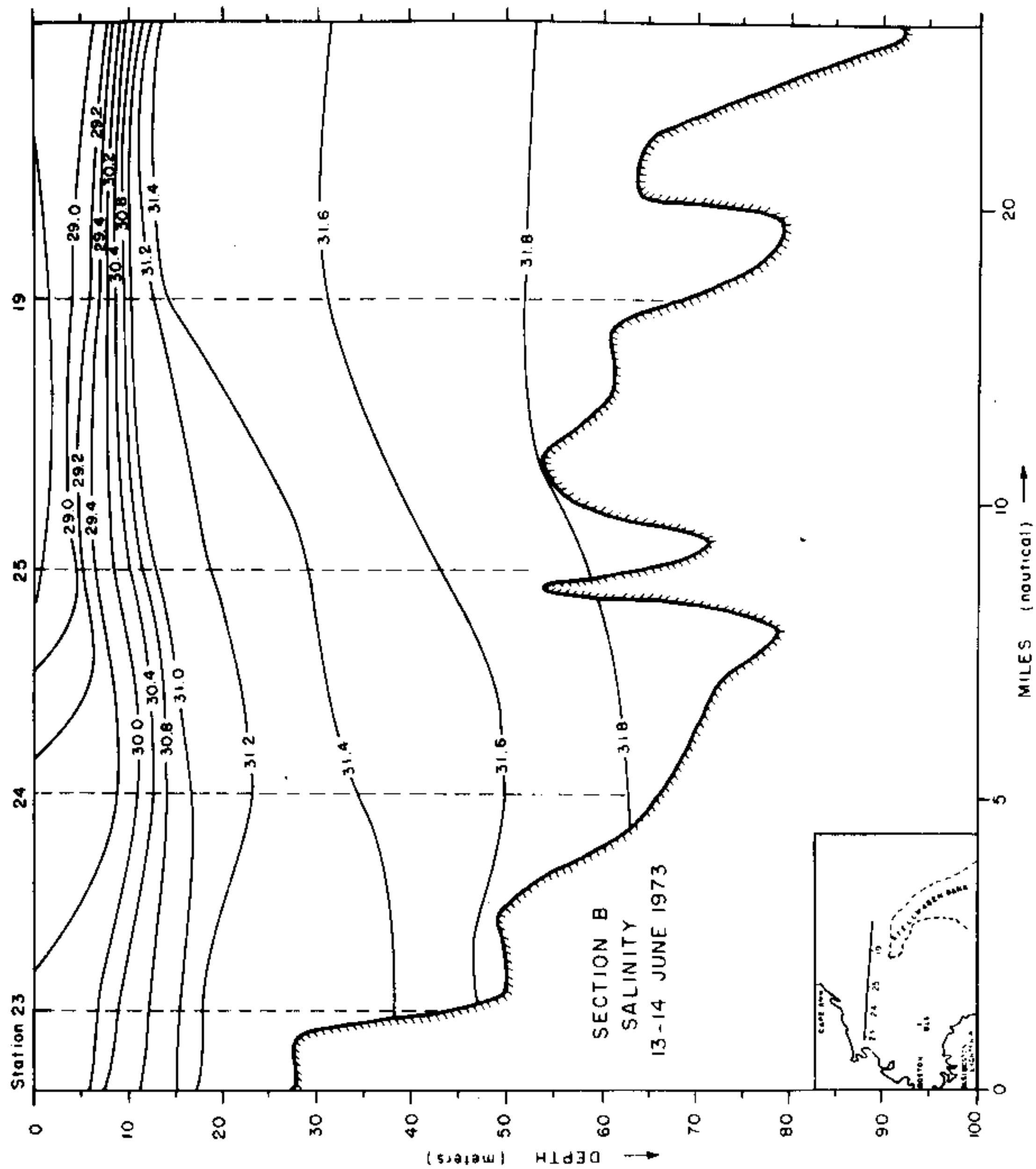
SECTION B
SALINITY
13-14 JUNE 1973
Station 23
24
25
19
DEPTH (meters)
MILES (nautical)

Figure 3.19

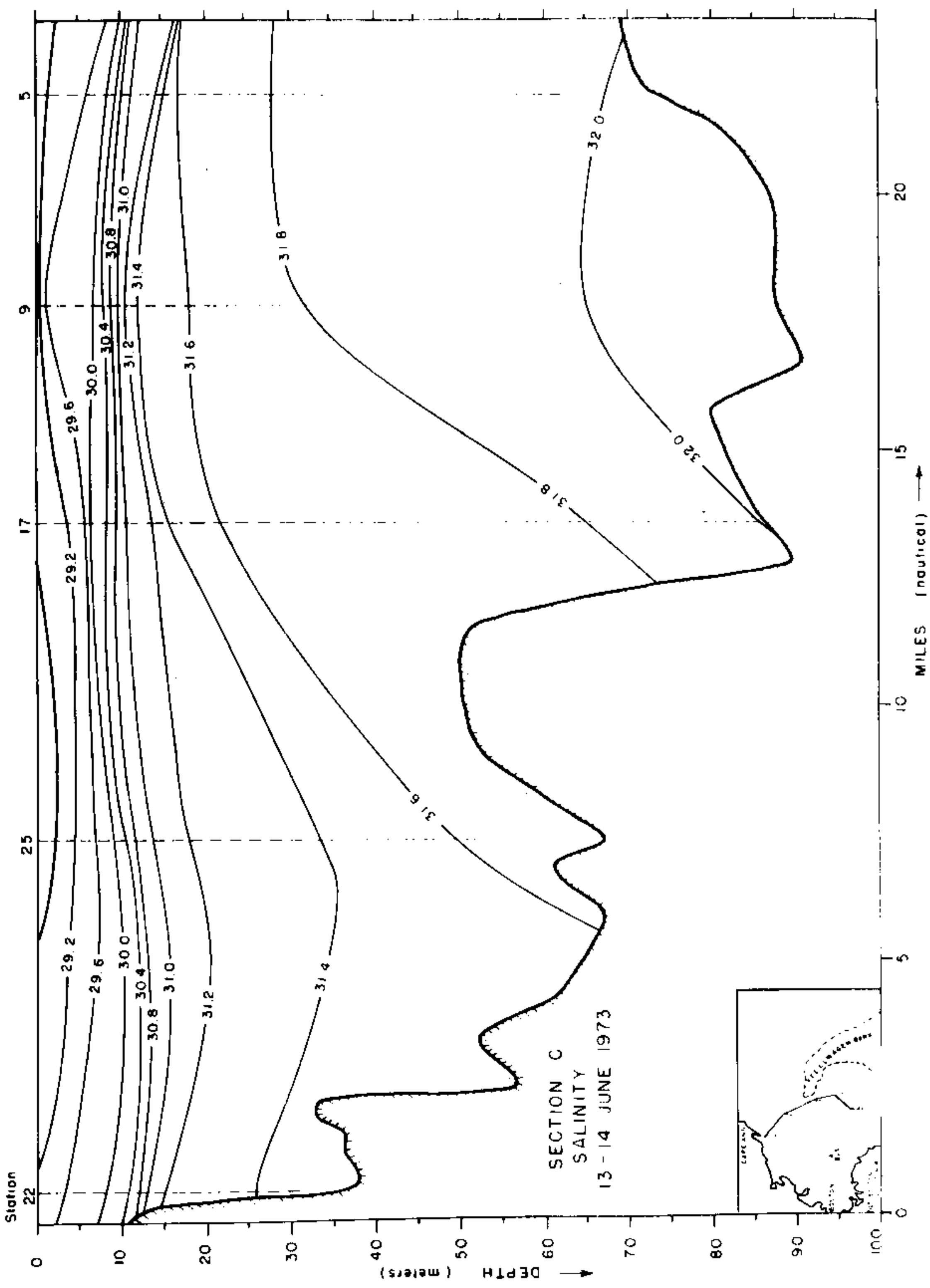
Station
22
25
17
9
5
DEPTH (meters)
0
10
20
30
40
50
60
70
80
90
100
MILES (nautical)
0
5
10
15
20
SECTION C
SALINITY
13 - 14 JUNE 1973
29.2
29.6
30.0
30.4
30.8
31.0
31.2
31.4
31.6
31.8
32.0

Figure 3.20

CHAPTER 4

VOLUMETRIC DETERMINATION OF FRESH WATER IN THE BAY

It is unfortunate that the first planned cruise of 14-15 March had to be aborted due to rough weather and equipment failure, since by the time of the first actual cruise two weeks later the homogeneous conditions, typical of the Bay in winter (Bigelow, 1927), had been eroded. Because of this we have no actual record of the base salinity of the water of the Bay with which the fresh water from the rivers mixed.

For this study the homogeneous winter salinity of the water of the Bay was assumed to be 32.2 $^0/00$. There are many reasons that led to the choosing of 32.2 $^0/00$ water for the winter salinity; it is observed that the bottom waters of the Bay at 29-30 March had a salinity of 32.2 $^0/00$ (see Fig. 3.6). In Fig. 3.1 it is seen that the patch of high salinity water in the middle of the Bay on 29-30 March is centered at station 17 of that cruise. The variation of salinity with depth at this point is shown in Appendix C, Fig. 1.

It is observed that the salinity changes from 31.7 $^0/00$ at the top to 32.2 $^0/00$ at the bottom; a similar observation is noted at station 11 (see Appendix C, Fig. 2) which is also in this pool of high salinity water. This difference of only .5 $^0/00$ from top to bottom contrasts greatly with the other stations of this cruise, where the variation from top to bottom is of the order of 1.1 $^0/00$ (for example, stations 16 and 18, just 7 km to the west and east respectively, of station 17) (see Appendix C, Figs. 3 and 4).

Chase (1969) shows that the average surface salinity at the Boston Lightship over a 12 year period (1956-1967) was 32.2 $^0/00$. This reinforces the belief that the winter homogeneous salinity for 1973 was 32.2 $^0/00$ and that the error in this figure is no more than the error in determining the average salinity of the Bay from the vertical casts. In any case, the choice of the "base-line" salinity in no way affects the volume of fresh water added between any two cruises, although it does affect the total amount of fresh water believed to be in the Bay.

To determine the amount of fresh water in the Bay, the method used was similar to that used by Ketchum and Keen (1955) to determine the accumulation of river water on the continental shelf between Cape Cod and Chesapeake Bay. The Bay was divided into four sections, A, B, C, and D (see Fig. 4.1). The volume of each section was determined by use of the depth readings on the U.S. Coast and Geodetic Survey Navigation Chart #1207. These values are shown in Table 4.1.

The depth mean salinity was then determined for each section (see Tables 4.2 - 4.6) by finding the average salinity in the water column at each station in the section. The fraction of fresh water in the Bay, f, at any given time is given by

$$f = \frac{S_o - \bar{S}}{S_o} \qquad 4.1$$

where S_o is the original salinity of the water in the Bay and $\bar{S}$, the average salinity in the Bay at a given time (Ketchum and Keen, 1955) (see Appendix D). This model assumes that the total volume of water in the Bay remains constant, as the fresh water is added. This assumption is a reasonable one since the amount of fresh water in the Bay was less than 3% of the total volume of water in the Bay.

To determine the volume of fresh water in each section, the fraction of fresh water was multiplied by the total volume of each section (see Tables 4.2 - 4.6). The sum of the fresh water in each section gave the total amount of fresh water in the Bay. The total volume of fresh water in the Bay at the time of any given cruise was subtracted from the volume there at the time of the previous cruise to obtain the volume of fresh water added to the Bay during the time between the two cruises (see Tables 4.2 - 4.6).

Computing the average salinity of a volume of water as large and as irregularly shaped as Massachusetts Bay is at best a rough estimate. Since a vertical profile was obtained on the average of every 7 km on each of these cruises (see Fig. 3.1 - 3.5), a fairly good estimate was made (see Appendix D). This estimate is believed to be accurate to ± .05 $^0/00$. However, since in determining the fraction of fresh water (Eqn. 4.1) a difference between two large numbers is required, it is believed that the fresh water volume is accurate to within 25% at the time of the first cruise when the salinity difference is small, and to within 10% at the time of the last three cruises when the salinity difference is much greater (see Tables 4.2 - 4.6). The volume of fresh water present in the Bay, at any given time, is shown in Fig. 4.2.

The daily discharge of water was plotted for the Neponset, Charles and Mystic Rivers, the Mother Brook and the Deer Island Sewerage treatment plant, as the sources of fresh water which empty into the Bay directly

TABLE 4.1

VOLUME OF BAY

	A	B	C	D	Total
Volume ($m^3 \times 10^6$)	15,420	21,264	19,404	22,405	78,493

TABLE 4.2

VOLUME OF FRESH WATER IN BAY, 29-30 MARCH, 1973

Section	A	B	C	D	Total
Average Salinity ($\bar{S}$) $^0/_{00}$	31.7	31.8	31.8	31.9	
Fraction Fresh (f)	.0155	.0124	.0124	.0093	
Volume of Fresh Water ($m^3 \times 10^6$)	239	264	241	208	952

TABLE 4.3

VOLUME OF FRESH WATER IN BAY, 21-22 APRIL 1973

	A	B	C	D	Total
Average Salinity ($\bar{S}$) $^0/_{00}$	31.5	31.45	31.35	31.30	
Fraction Fresh (f)	.0217	.0232	.0263	.0280	
Volume of Fresh Water ($m^3 \times 10^6$)	335	493	510	627	1965
Volume Added between 29-30 March to 21-22 April ($m^3 \times 10^6$)	106	229	269	419	1047

TABLE 4.4

VOLUME OF FRESH WATER IN BAY, 5-6 MAY 1973

	A	B	C	D	Total
Average Salinity ($\bar{S}$) $^0/_{00}$	31.25	31.30	31.20	31.25	
Fraction Fresh (f)	.0295	.0280	.0311	.0295	
Volume of Fresh Water ($m^3 \times 10^6$)	455	595	604	661	2,315
Volume Added between 21-22 April to 5-6 May ($m^3 \times 10^6$)	120	102	94	34	350

TABLE 4.5

VOLUME OF FRESH WATER IN BAY, 2-3 JUNE 1973

	A	B	C	D	Total
Average Salinity ($\bar{S}$) $^0/00$	31.25	31.25	31.25	31.15	
Fraction Fresh (f)	.0295	.0295	.0295	.0326	
Volume of Fresh Water ($m^3 \times 10^6$)	455	627	572	730	2,384
Volume Added between 5-6 May to 2-3 June ($m^3 \times 10^6$)	0	32	-32	69	69

TABLE 4.6

VOLUME OF FRESH WATER IN BAY, 13-14 JUNE 1973

	A	B	C	D	Total
Average Salinity ($\bar{S}$) $^0/00$	31.10	31.15	31.30	31.35	
Fraction Fresh (f)	.0342	.0311	.0280	.0264	
Volume of Fresh Water ($m^3 \times 10^6$)	527	661	543	592	2,323
Volume Added between 2-3 June to 13-14 June ($m^3 \times 10^6$)	72	34	-29	-138	-61

(see Fig. 4.3 - 4.7). This data, except for the Deer Island treatment plant, was obtained from the U.S. Geological Survey. Unfortunately, for certain rivers the values for part of May and for June was not yet available. When this occurred, if there were any values for that month, the average for the month was used, and if there were no readings available for the month, the average for the same month for the previous year, 1972, was used. The periods for which this occurred are clearly marked in Fig. 4.3 - 4.7 and Fig. 4.9 - 4.11.

Similarly, the daily flow rate of the rivers which originate north of Cape Ann and come into Massachusetts Bay, the Merrimac, Parker, and Ipswich Rivers, were plotted in Fig. 4.9 - 4.11. The total daily flow rate from these rivers is shown in Fig. 4.12. The salinity of the river water is taken as 0 $^0/00$, being at most .1 $^0/00$, (John Edmonds, 1973). The daily flow rates shown in Fig. 4.3 - 4.13 have been corrected for the drainage area which lie below the position of the gauging stations. The correction factors used, obtained from Mr. G. Searles at the Geological Survey, together with the gauged drainage area and total drainage area, are shown in Table 4.7.

The data for the Deer Island sewerage treatment plant was obtained from the plant at Deer Island. The measured salinity during the period January - June, 1973, of the Deer Island water was 5.5 $^0/00$. Therefore, this volume of water was divided into two components, of 0 $^0/00$ and 32.2 $^0/00$ salinity respectively. The 0 $^0/00$ component constitutes the effective fresh water present in the Deer Island discharge, while the 32.2 $^0/00$ component would have no effect on the Bay since 32.2 $^0/00$ was

TABLE 4.7

CORRECTION FACTORS FOR RIVER DISCHARGE

River	Drainage Area above Gauging Station	Total Drainage Area	Correction Factor
Merrimac	4,633	5,006	1.08
Parker	21.5	65	3.00
Ipswich	124	155	1.25
Mystic	23	65	2.5
Charles	251	299	1.2
Neponset	62.4	117	2.0
*Mother Brook	251*	299*	1.2

*The Mother Brook is partly a man made canal linking the Charles River with the Neponset River, but the gauging station on the Charles does not record the amount of water flowing through the Mother Brook, hence the same correction factor as for the Charles River is used.

taken as the original salinity of the Bay. The total daily flow of fresh water from the sources which empty into the Bay directly is shown in Fig. 4.8. The total daily flow of fresh water into the Bay from all sources considered is plotted in Fig. 4.13.

In order to compare the volume of fresh water in the Bay with the discharge of the rivers it was necessary to determine the time lag between the time the water left the river and the time it got into the Bay. For the case of the rivers which empty into the Bay directly, the time lag would be zero. This, however, would not be the case for rivers north of Cape Ann. Since by far the largest contribution to the total flow (Fig. 4.13) is the Merrimac (Fig. 4.9), it is essential that a good estimate of this time lag is obtained.

By aligning the maximum flow rate for the rivers north of Cape Ann (Fig. 4.12) with the maximum volume of fresh water in the Bay (Fig. 4.2), a time lag of 20 days was determined. This figure of 20 days compares favorably with the drift bottle measurements of Day (1958), Bumpus (1961), and Graham (1970), all of whom gave a surface drift of between 2 - 4 km/day. Therefore, to determine the flow of fresh water from north of Cape Ann into the Bay, the river discharge 20 days prior to the period being considered was taken.

It was also necessary to determine at what rate the Bay was losing the fresh water it contained. By examination of Fig. 3.1 - 3.5, it seemed that the Bay lost the fresh water not by advection out of the Bay, but by diffusion of salt into the Bay. Although an influx of salt is mainly responsible for the disappearance of the fresh water, this will still be termed as a loss of fresh water. In Fig. 4.2 of the volume of fresh water in the Bay versus time, it is observed that the volume of fresh water in the Bay reaches a maximum of 2,450 x 10^6 m^3 on May 25. Since on this date the volume of fresh water in the Bay was neither increasing nor decreasing, it meant that the volume of fresh water added to the Bay was equal to the volume of fresh water being lost. When the twenty day lag was taken into account, it means that for the rivers north of Cape Ann the discharge of May 5 was required. Unfortunately in the period from 30 April - 8 May no readings were recorded for the Merrimac and the average discharge for the month of May had to be used to determine the flow on May 5. The value so obtained is shown in Table 4.8.

The rate of diffusion of salt into the Bay would be dependent on the total volume of fresh water in the Bay. Assuming that this is a linear relationship which is consistent with the total mixing model used in computing the volume fresh water, the average loss per day over any given time period is obtained from the average volume of fresh water in the Bay over that period. In Table 4.8 the values of volume of fresh water added in the periods between each cruise as calculated from the volume of river run-off, together with the volume of water observed to be added, computed from the average salinity of the Bay, are shown. There is surprisingly good correspondence between both values, their discrepancy at no time being greater than the possible percentage error in determining the total volume of fresh water in the Bay by the method of Ketchum and Keen (1955).

TABLE 4.8

VOLUME OF FRESH WATER IN BAY

Time Period	Average Volume in Bay ($m^3 \times 10^6$)	Average Loss Per Day ($m^3 \times 10^6$)	Period (days)	Total Loss (L) ($m^3 \times 10^6$)	River Flow Volume (R) ($m^3 \times 10^6$)	Volume Added to Bay Using River Data (R-L) ($m^3 \times 10^6$)	Volume Added to Bay Using Method of Ketchum and Keen ($m^3 \times 10^6$)
May 25	2,450	50.8	1	50.8	50.8	0	0
29-30 March to 21-22 April	1,476	30.6	23	704	1,671	976	1,047
21-22 April to 5-6 May	2,157	44.7	14	655	1,281	626	587
5-6 May to 2-3 June	2,354	48.8	28	1,366	1,278	-88	69
2-3 June to 13-14 June	2,354	48.8	11	537	626	89	-61

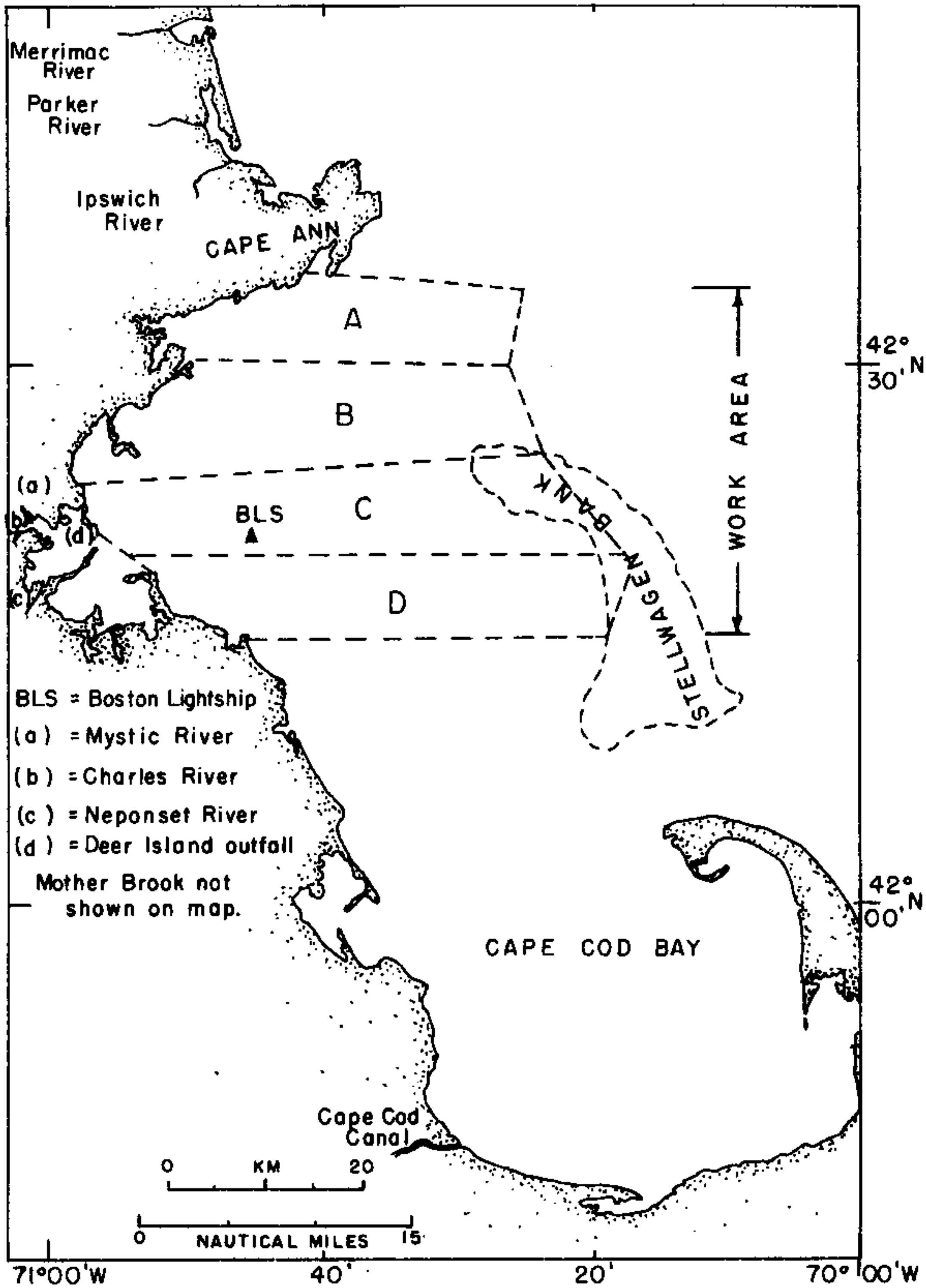

Figure 4.1: Map of Massachusetts Bay showing Region of Work and Sections into which Bay was divided to compute the Volume of Fresh Water

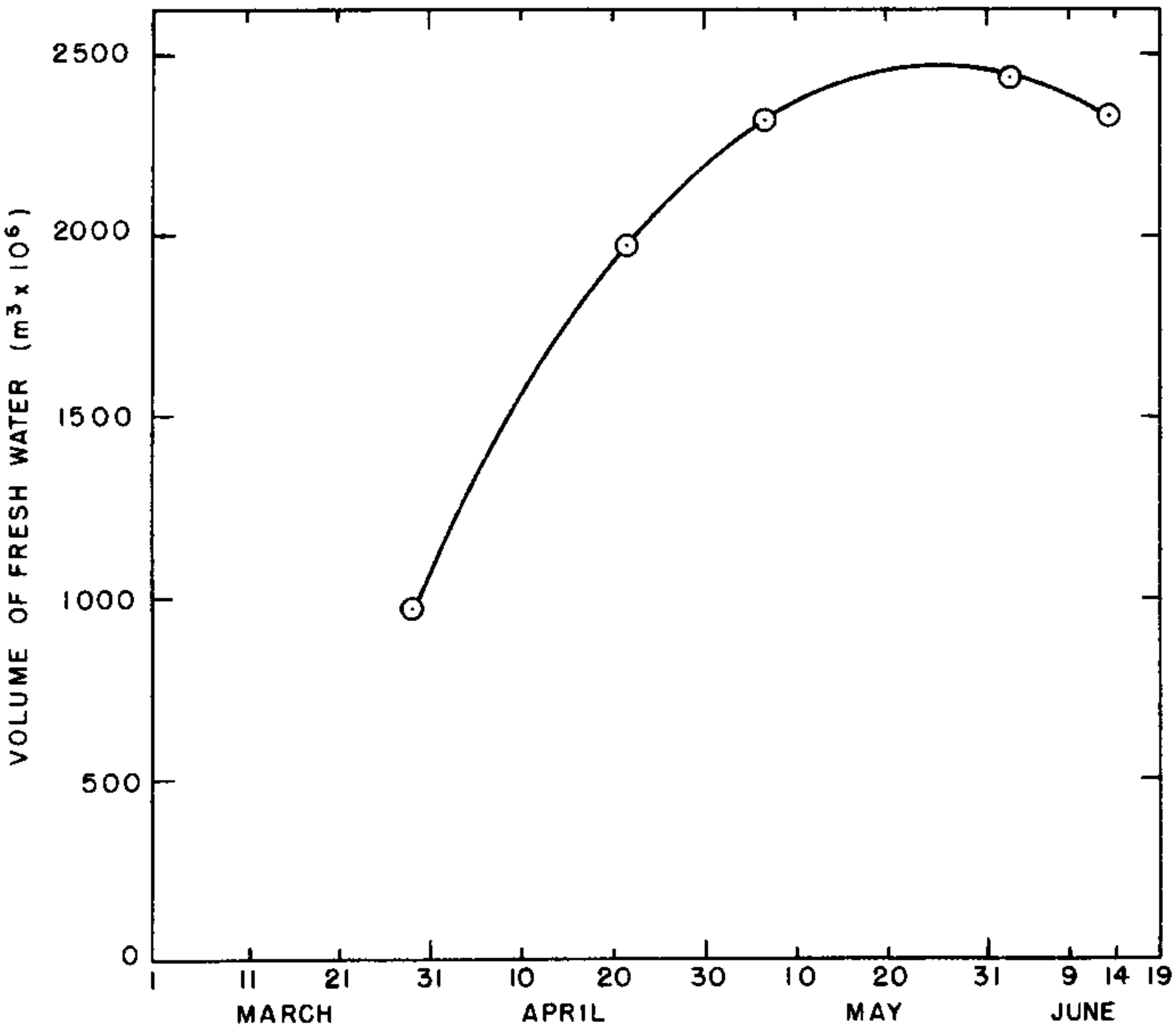

Figure 4.2: Total Volume of Fresh Water in Bay vs Time

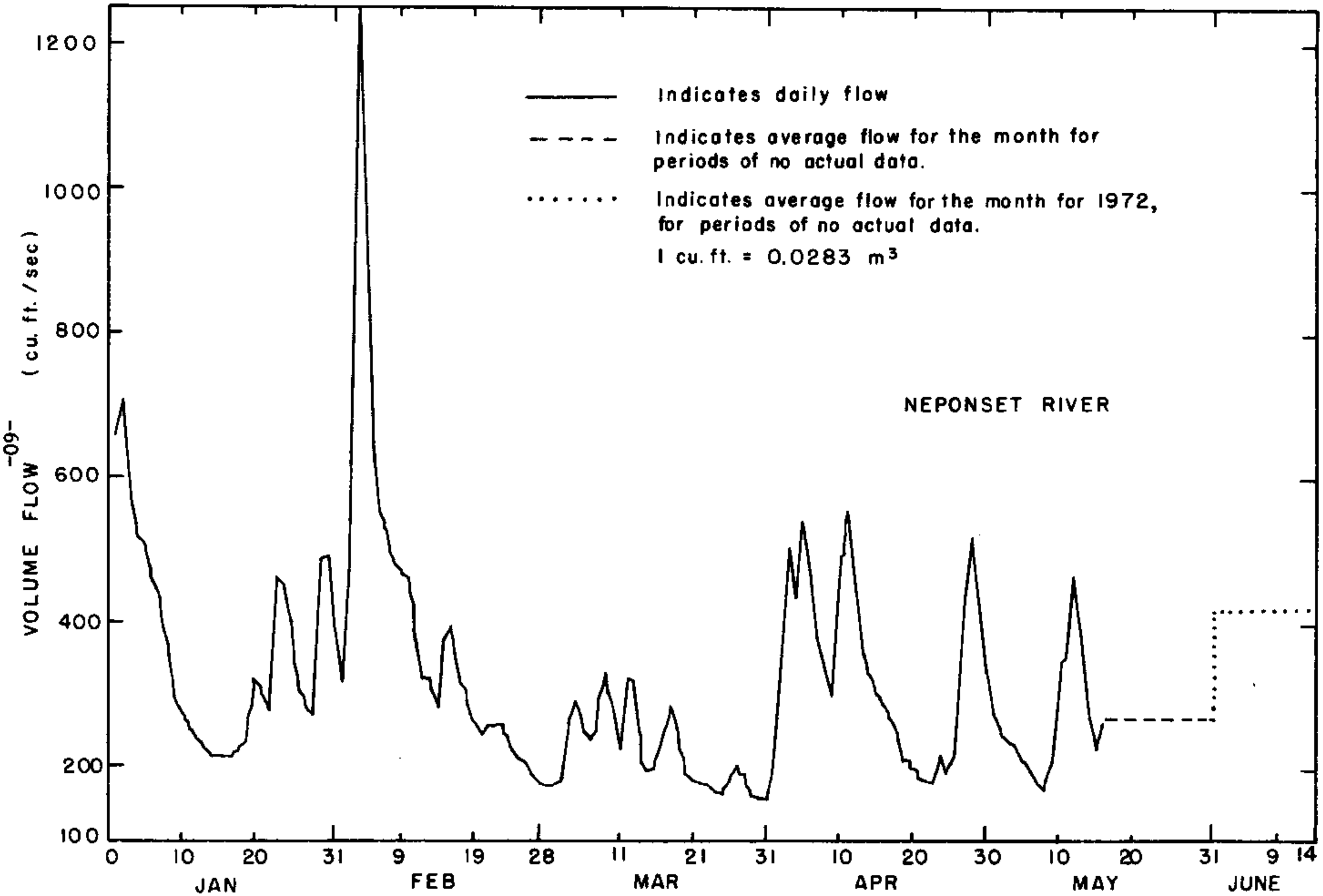

Figure 4.3: Daily Volume Flow of Neponset River

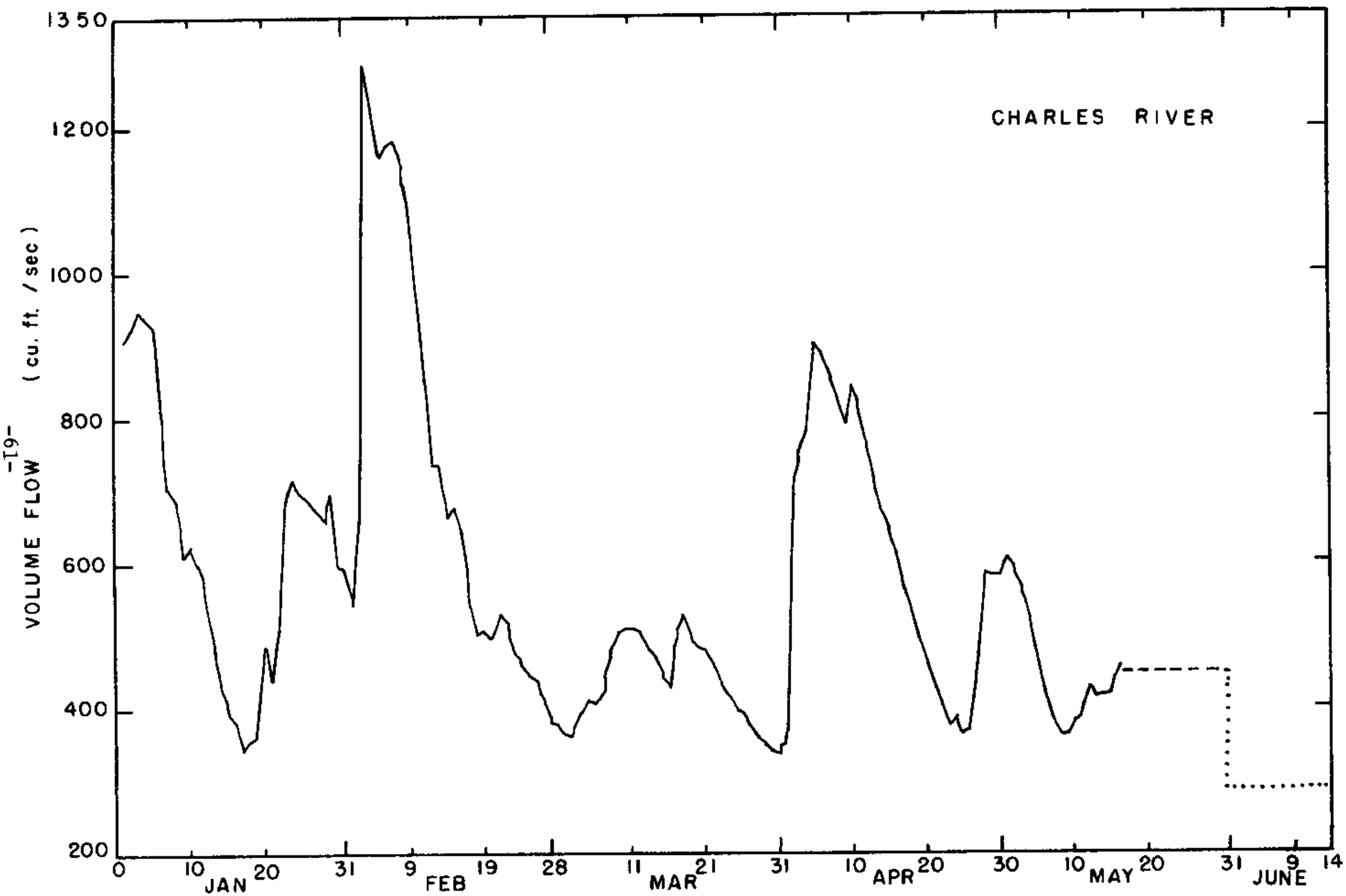

Figure 4.4: Daily Volume Flow of Charles River

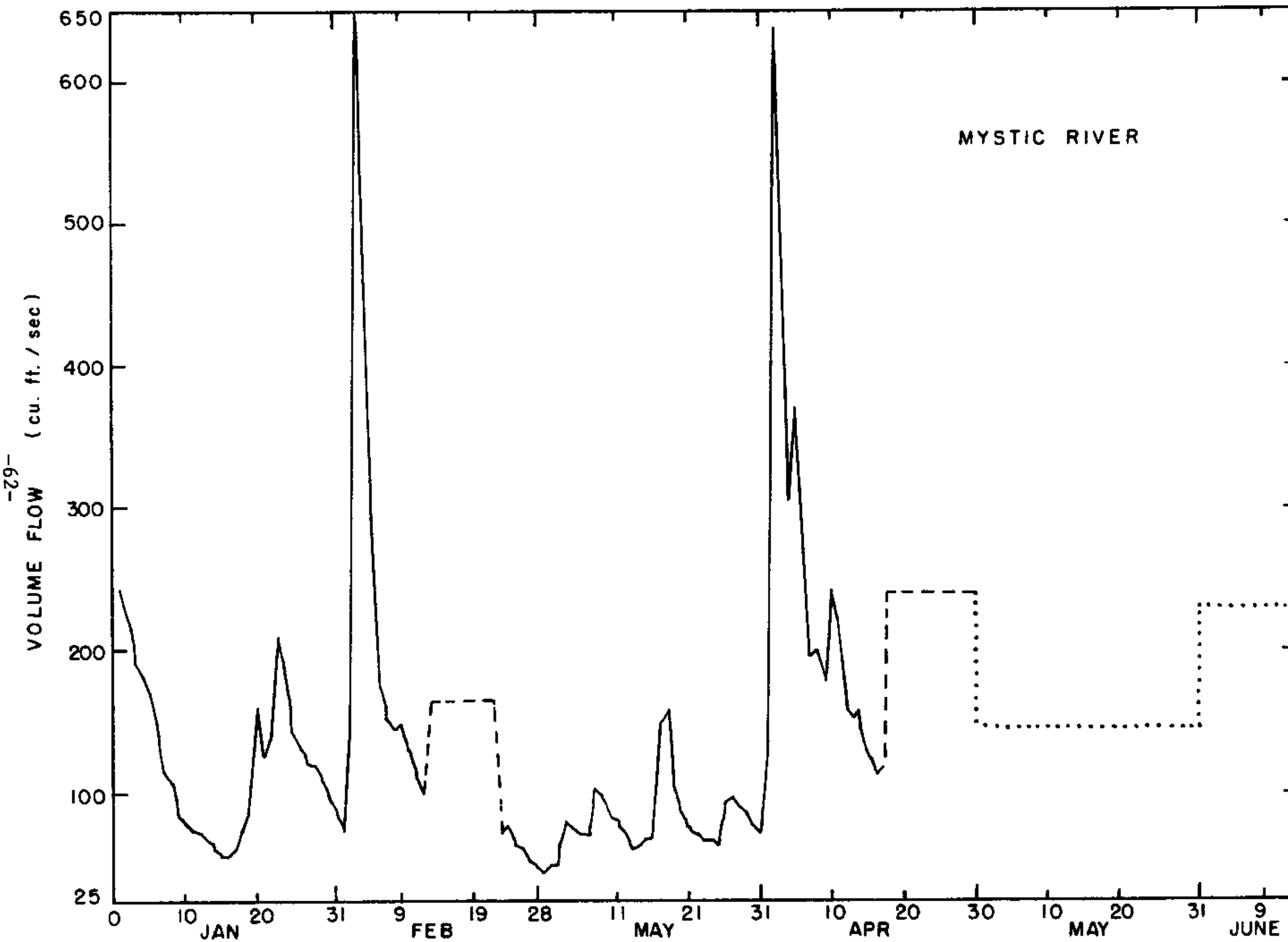

Figure 4.5 Daily Volume Flow of Mystic River

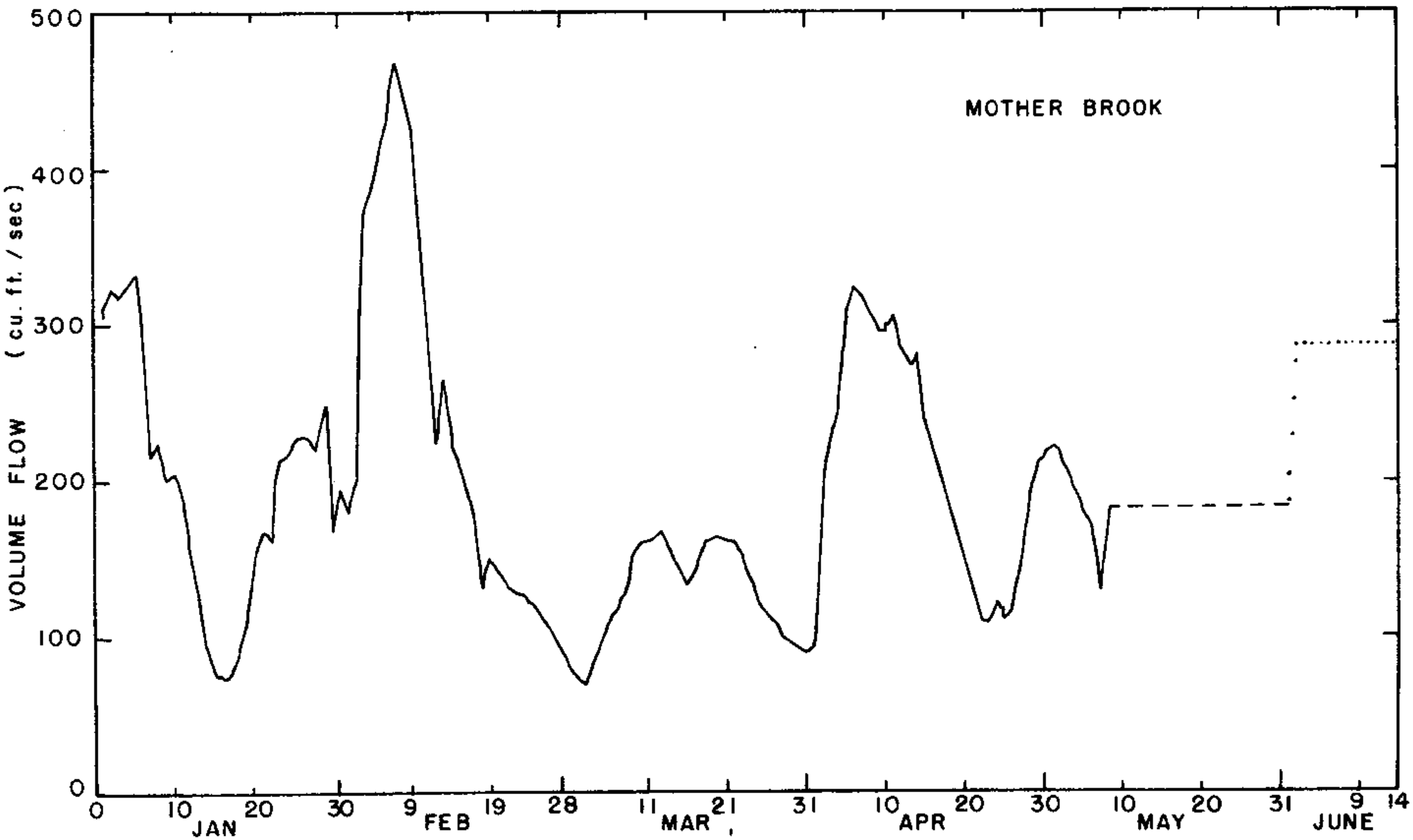

Figure 4.6: Daily Volume Flow of Mother Brook

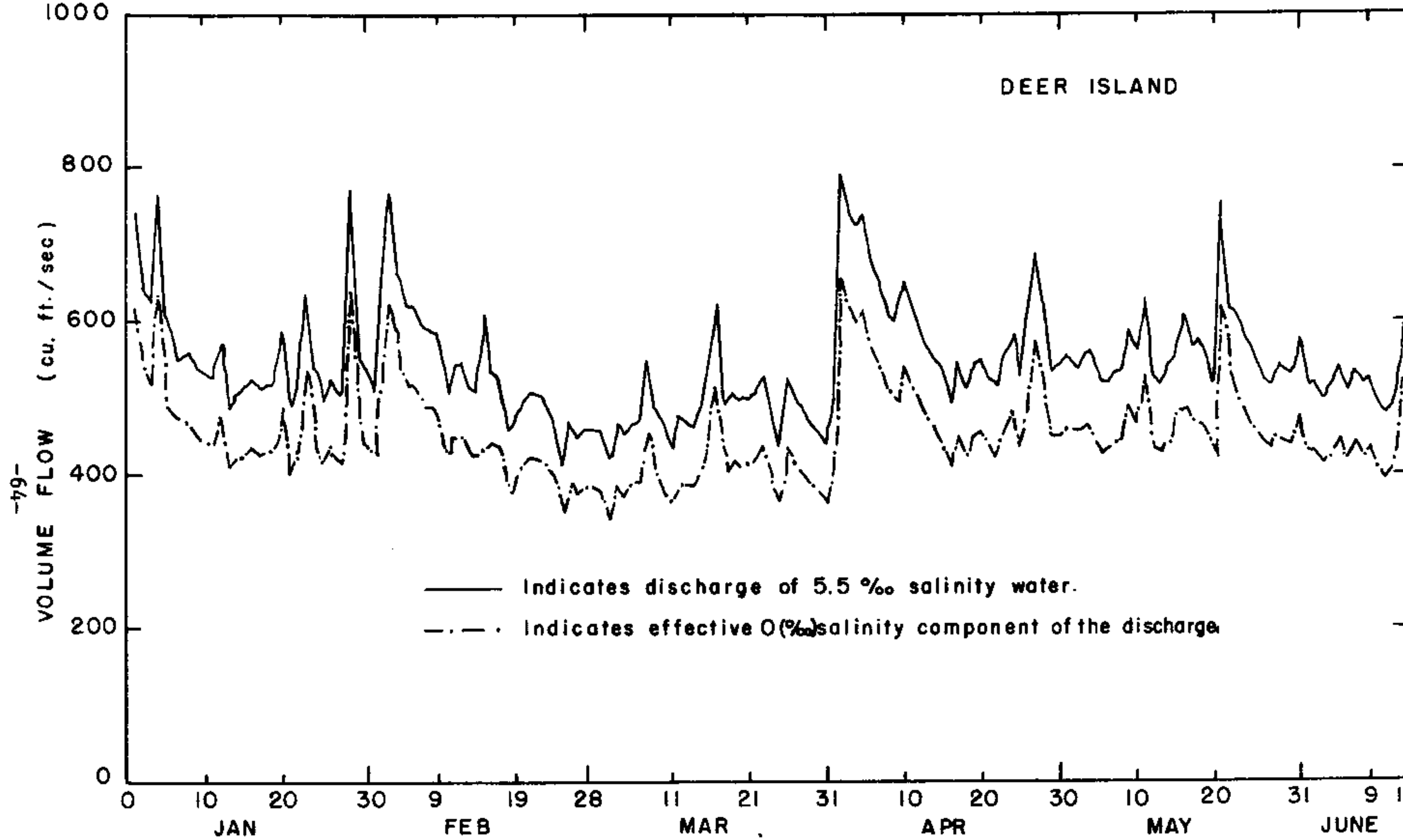

Figure 4.7: Daily Volume Flow of Deer Island Sewerage Treatment Plant

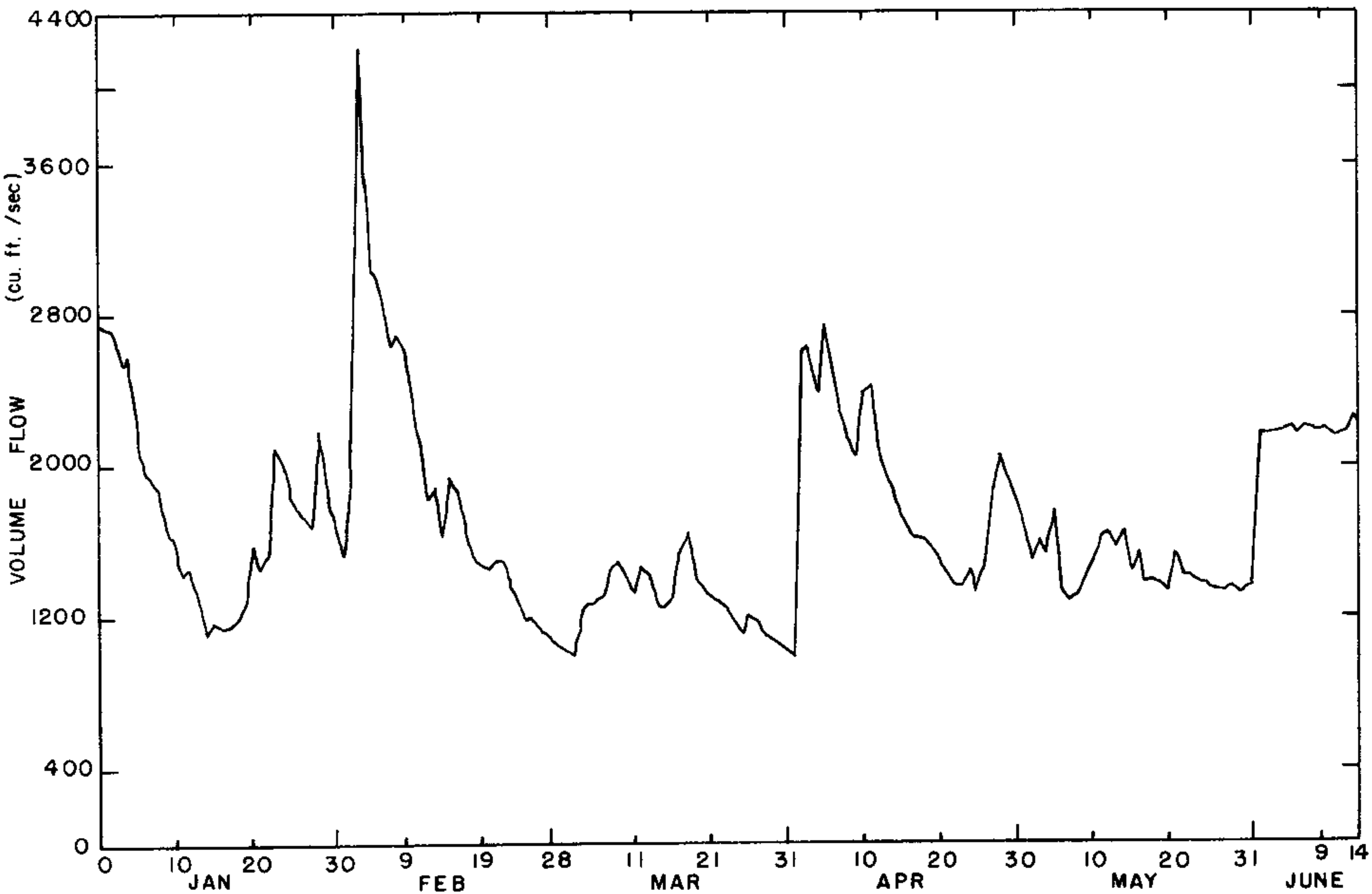

Figure 4.8: Daily Volume Flow of Fresh Water into Massachusetts Bay from Sources Which Empty into the Bay Directly

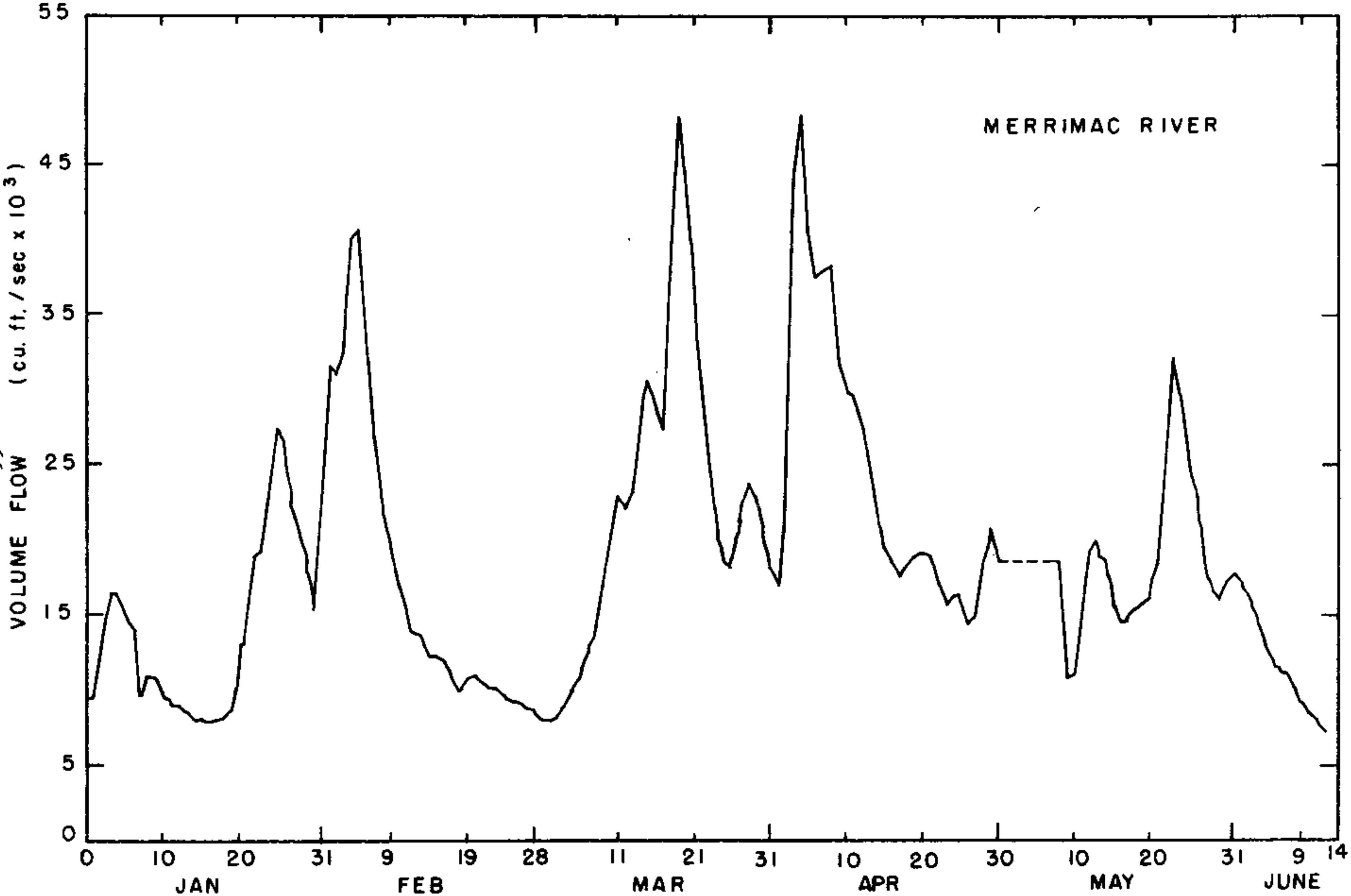

Figure 4.9: Daily Volume Flow of Merrimac River

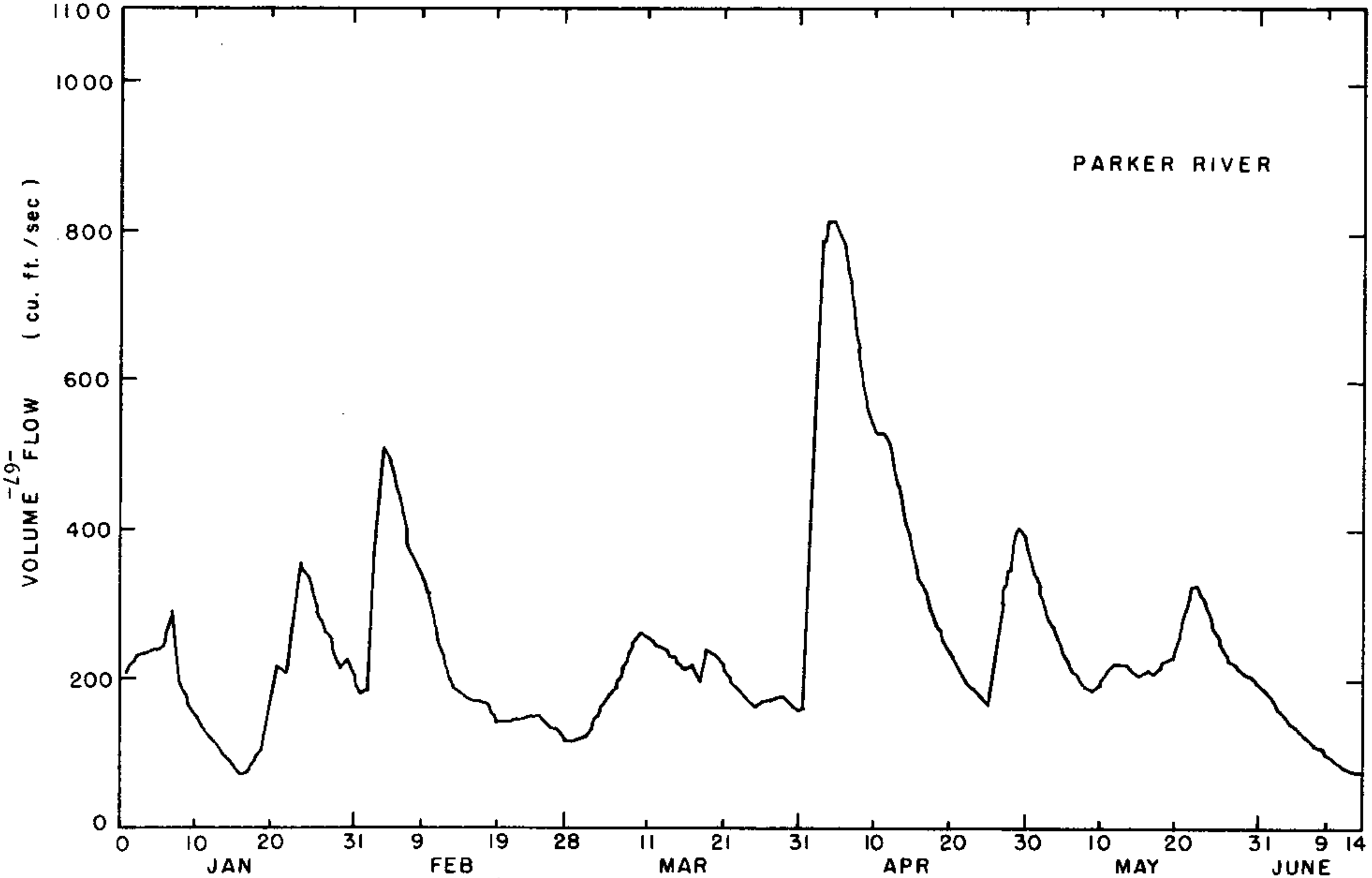

Figure 4.10: Daily Volume Flow of Parker River

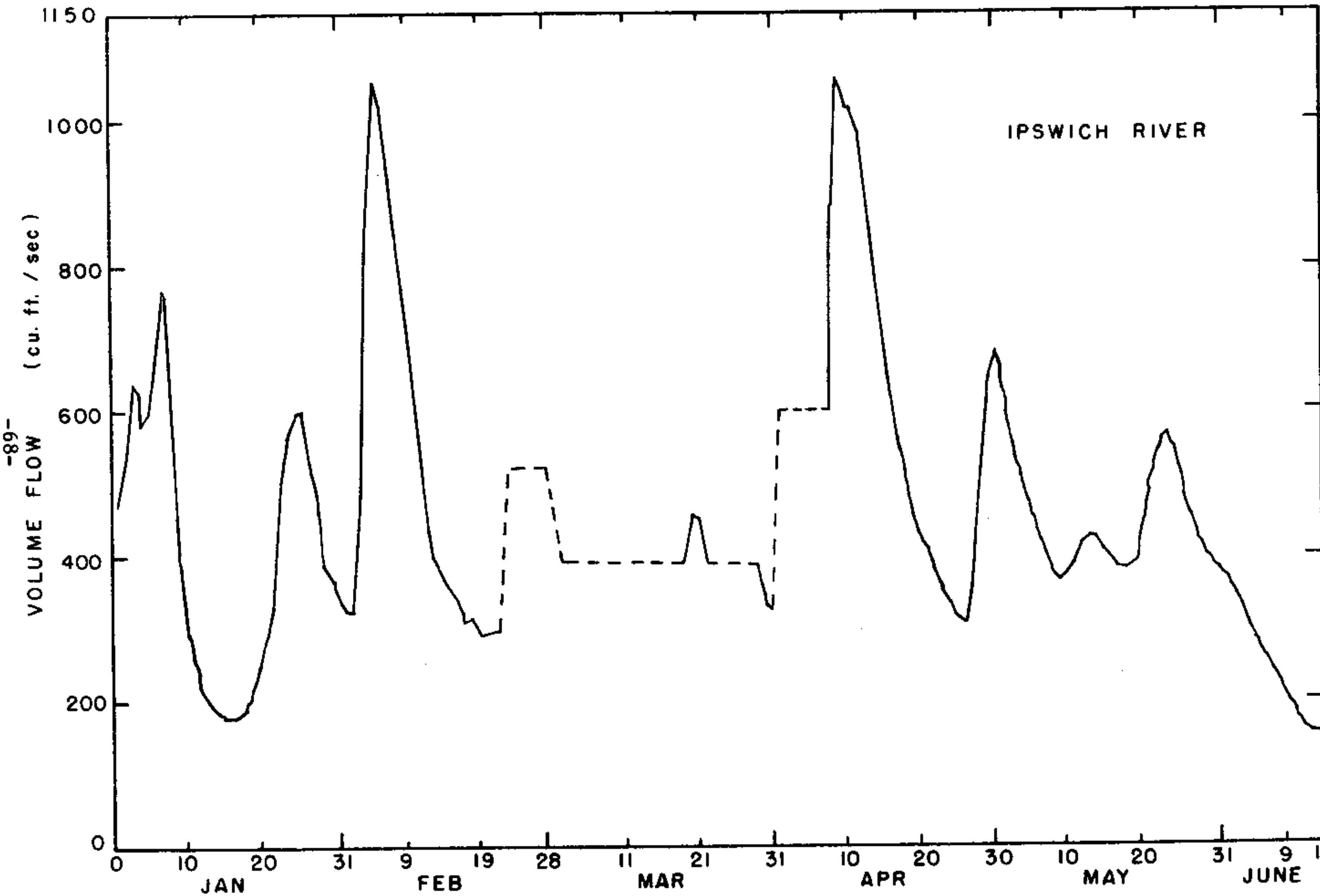

Figure 4.11 Daily Volume Flow of Ipswich River

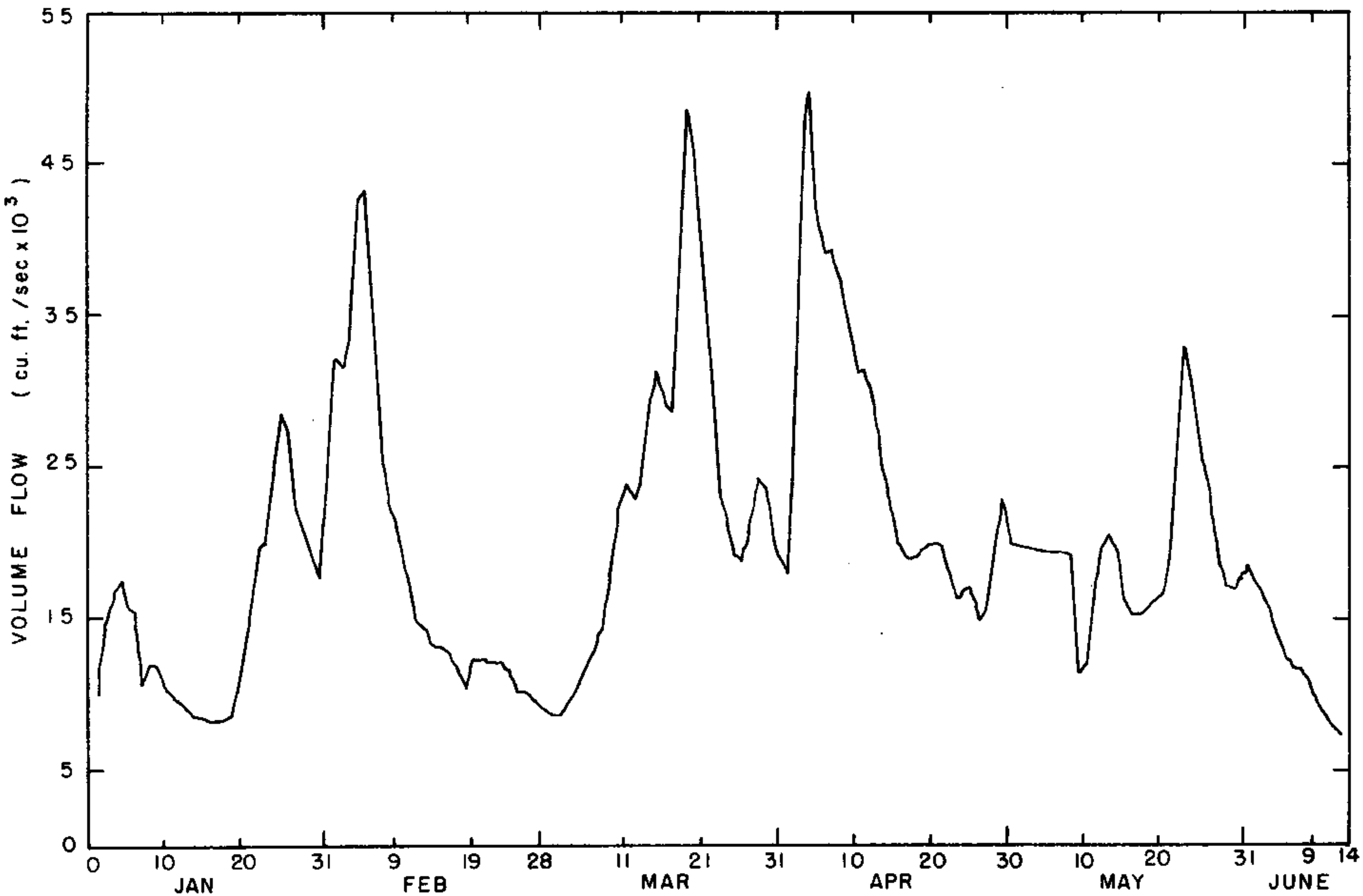

Figure 4.12: Total Daily Volume Flow of Fresh Water from Sources North of Cape Ann

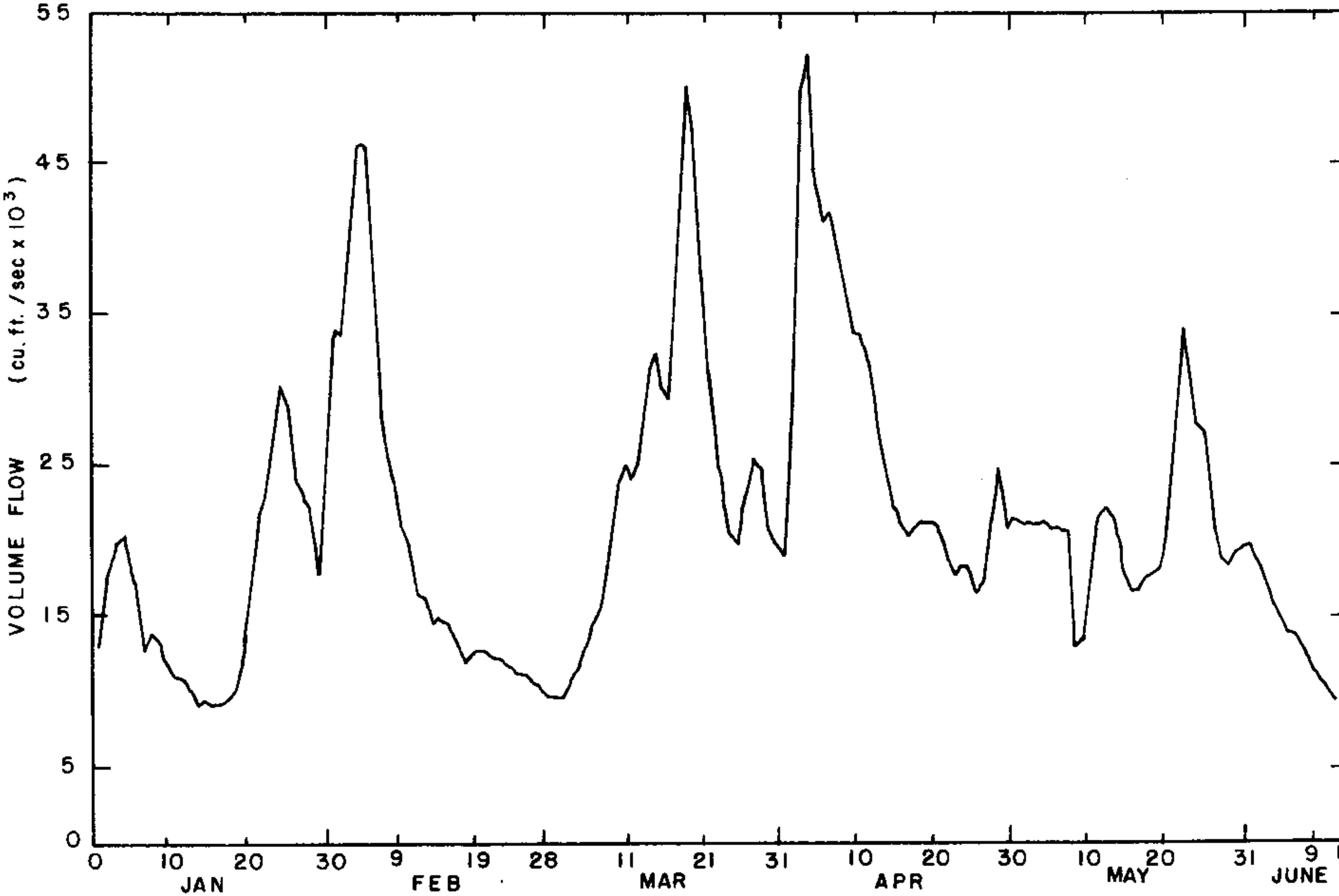

Figure 4.13: Total Daily Volume Flow of Fresh Water into Massachusetts Bay from All Sources

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

A. Conclusions

The major source of fresh water in the Bay was seen to be the Merrimac, which accounts for about 90% of the total discharge during the spring months. This water comes into the Bay in the form of a tongue of low salinity water in the middle of the Bay, and slowly spreads out to encompass the Boston Lightship to the west and as far out as Stellwagen Bank to the east.

During the early spring the freshening effect of the run-off is felt most in the upper twenty meters, while in the late spring the bottom waters start getting fresh. The salinity difference from top to bottom is most marked during this period; this difference being almost 0 $^{0}/_{00}$ during winter, and as great as 4.0 $^{0}/_{00}$ by May.

For the spring of 1973, the maximum amount of fresh water in the Bay was 2,450 x 10^6 m^3 which occurred on May 25. This day, May 25, can then be said to mark the end of the vernal freshening of the Bay. There was quite a good correspondence between the volume of fresh water found in the Bay and the volume of fresh water that came in via the rivers; the discrepancy between these two figures was at no time greater than the error in the figure of the volume of fresh water in the Bay computed by the method of Ketchum and Keen (1955).

B. Future Work

The data collected for the region studied can be used to determine a much more accurate picture of the dynamics of the Bay. It would be possible also to trace the development of the thermocline from the winter to the spring.

No account was taken in this analysis of the effect of evaporation from and precipitation onto the Bay. There is little data available to determine the amount of evaporation that takes place in the Bay, and this is one region where some work can be concentrated in the future. The tacit assumption used in determining the volume of fresh water in the Bay is that the effect of evaporation from the Bay is cancelled by the effect of direct precipitation on the Bay. Although previous estimates of these factors (Craig and Montgomery, 1949), show this to be a reasonable assumption, the data used was very scanty and it should be verified by further work.

APPENDIX A

```
C       THIS SUBROUTINE CALCULATES SALINITY
C       BASED ON THE COX, CULKIN, AND RILEY DATA
        SUBROUTINE SALIN(T,P,C,S)
         DOUBLE PRECISION RT
         S = 35.00
        T1 = T
         T2 = T1 * T1
         T3 = T2 * T1
         T4 = T3 * T1
         TD = T1 - 15.0
        P1 = P
         P2 = P1 * P1
         P3 = P2 * P1
         G = 1.5192 - 4.5302E-2 * T1 + 8.3089E-4 * T2 - 7.9E-6 * T3
         F = 1.042E-3 * P1 - 3.3913E-8 * P2 + 3.3E-13 * P3
         H = 4.0E-4 + 2.577E-5 * P1 - 2.492E-9 * P2
         AJ = 1.0 - 1.535E-1 * T1 + 8.276E-3 * T2 - 1.657E-4 * T3
         AL = 6.95E-3 - 7.6E-5 * T1
         SP = G * F + H * AJ
         RC = C / 42.909
         RT = 0.067652453D1 + 0.20131661D-1 * T1 + 0.99886585D-4 * T2
       1      - 0.19426015D-6 * T3 - 0.67249142D-8 * T4
   210 S0 = S
         AM = 35.0 - S
         RP = 1.0 + (1.0 + AL * AM) * SP * 1.0E-2
        RS=RC/(RT*RP)
         RS2 = RS * RS
         R15 = RS + 1.0E-5 * RS * (RS - 1.0) * TD * (96.7 - 72.0 * RS
       1    + 37.3 * RS2 - (0.63 + 0.21 * RS2) * TD)
         R152 = R15 * R15
         R153 = R152 * R15
         R154 = R153 * R15
         R155 = R154 * R15
         S = -0.08996 + 28.2972 * R15 + 12.80832 * R152 - 10.67869 * R153
       1    + 5.98624 * R154 - 1.32311 * R155
         IF (ABS(S-S0) -0.001) 220,210,210
   220 RETURN
         END
```

APPENDIX B

CALIBRATION CURVES FOR INSTRUMENTS USED

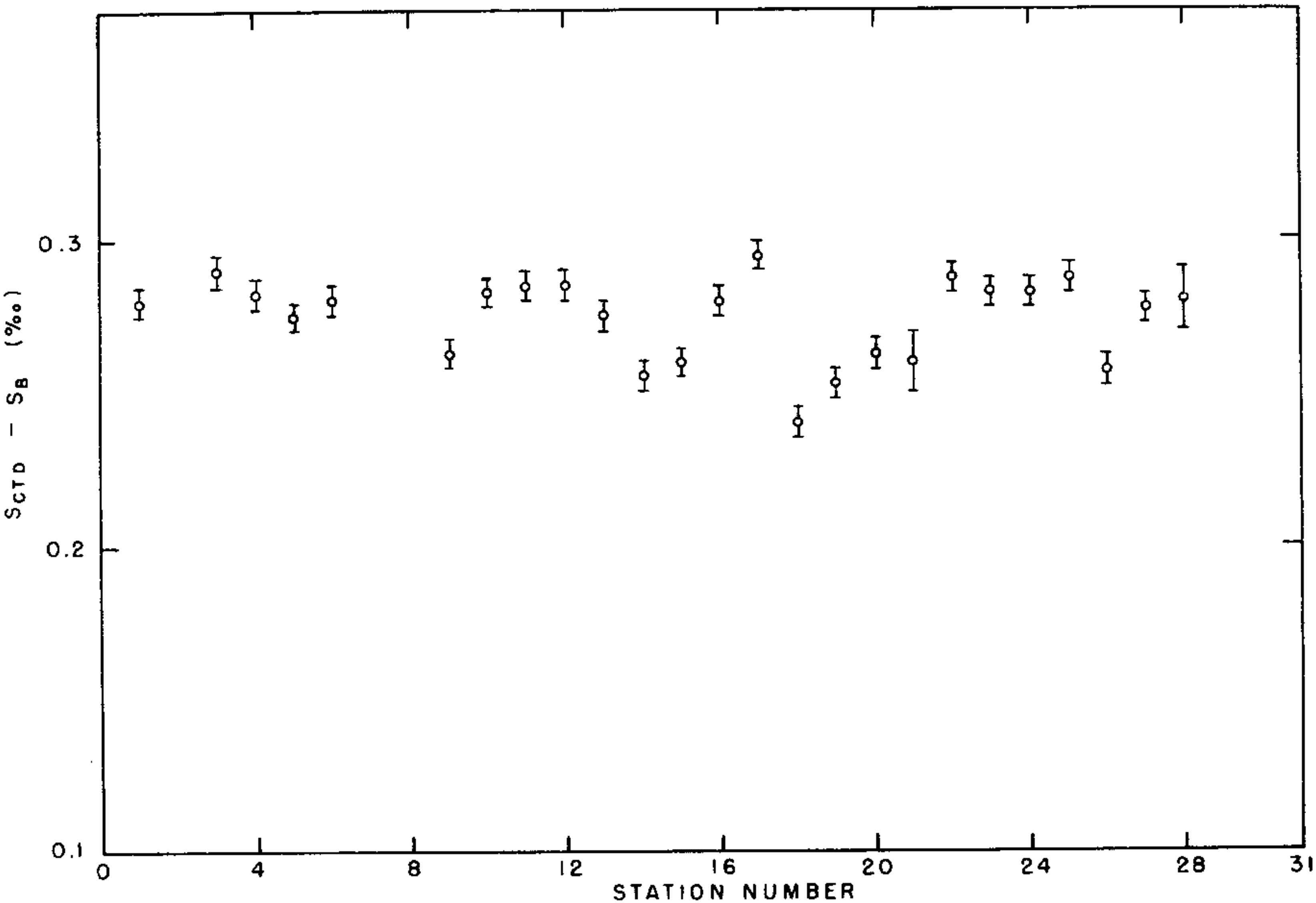

Figure 1: Difference of C.T.D. Reading from Bottle Reading vs Station Number. 29-30 March

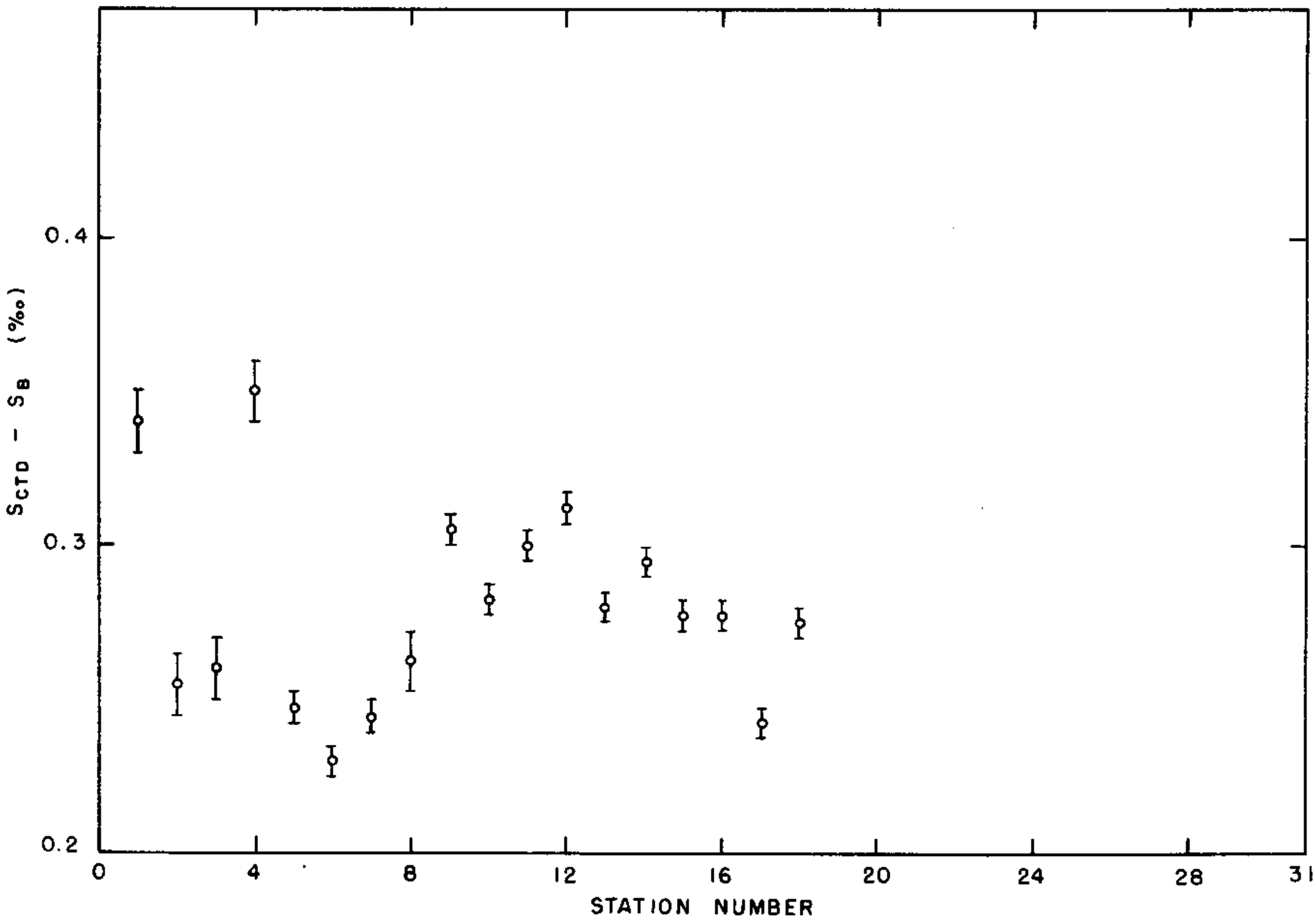

Figure 2: Difference of C.T.D. Reading from Bottle Reading vs Station Number. 14-15 April

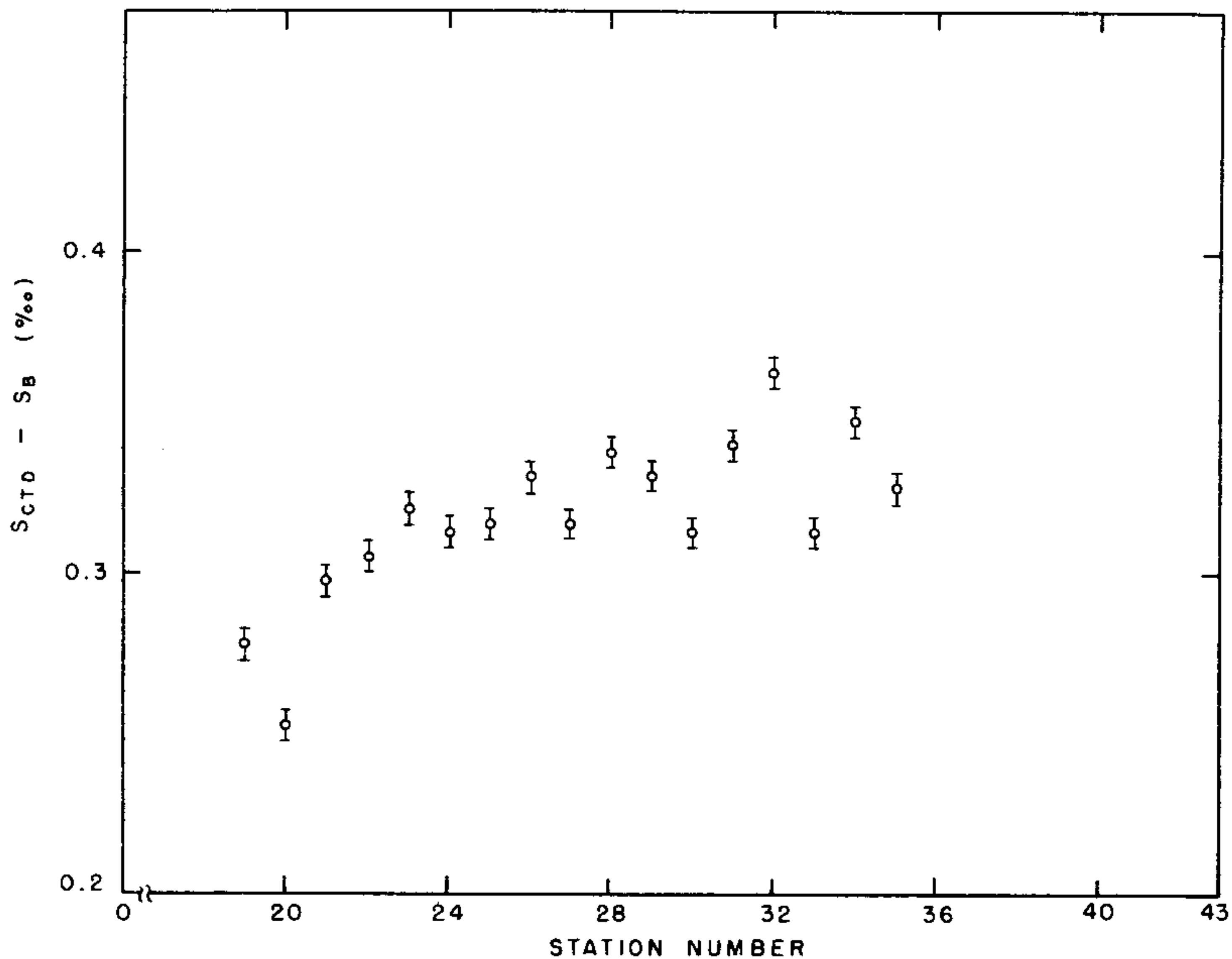

Figure 3: Difference of C.T.D. Reading from Bottle Reading vs Station Number. 21-22 April

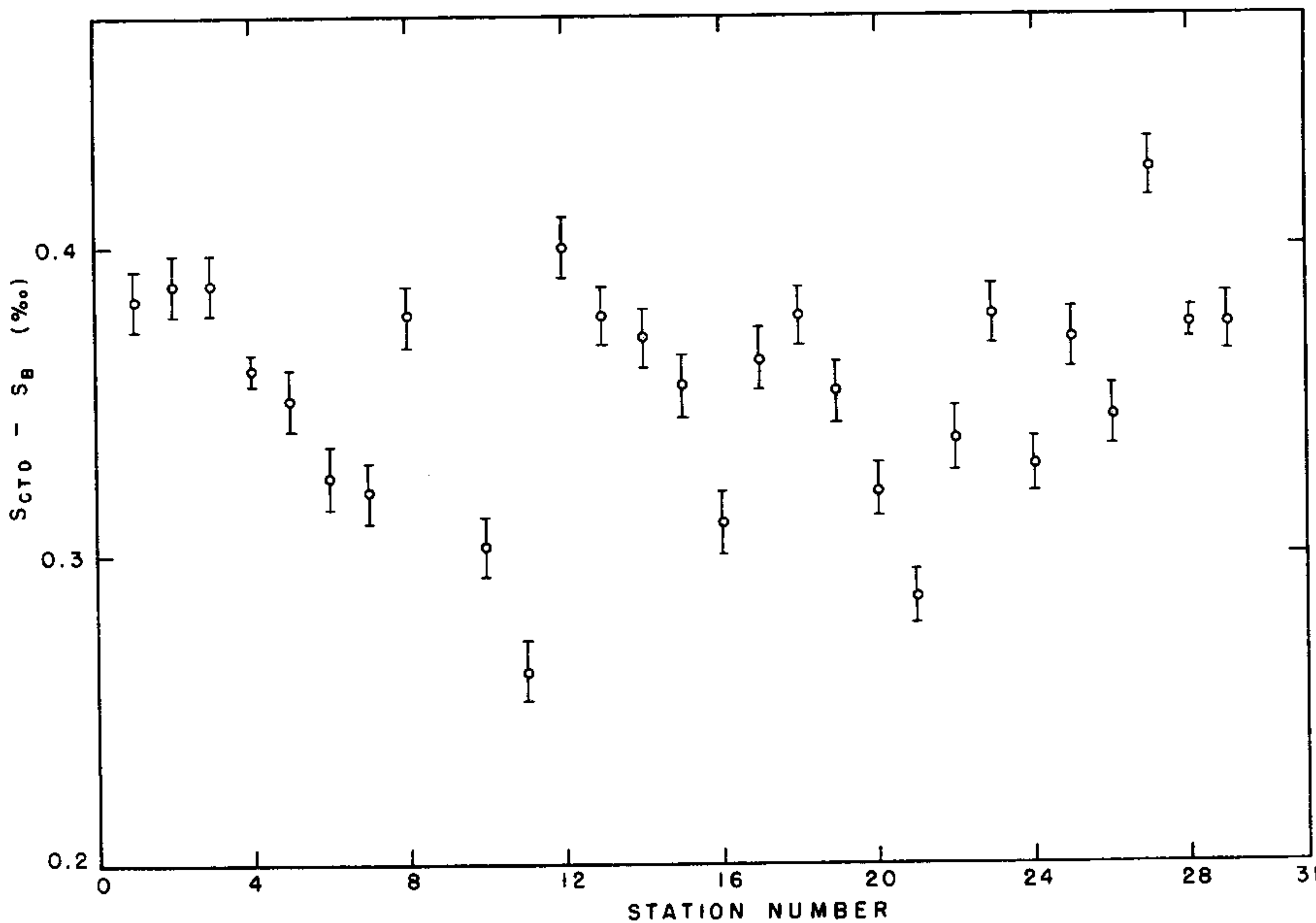

Figure 4: Difference of C.T.D. Reading from Bottle Reading vs Station Number. 5-6 May

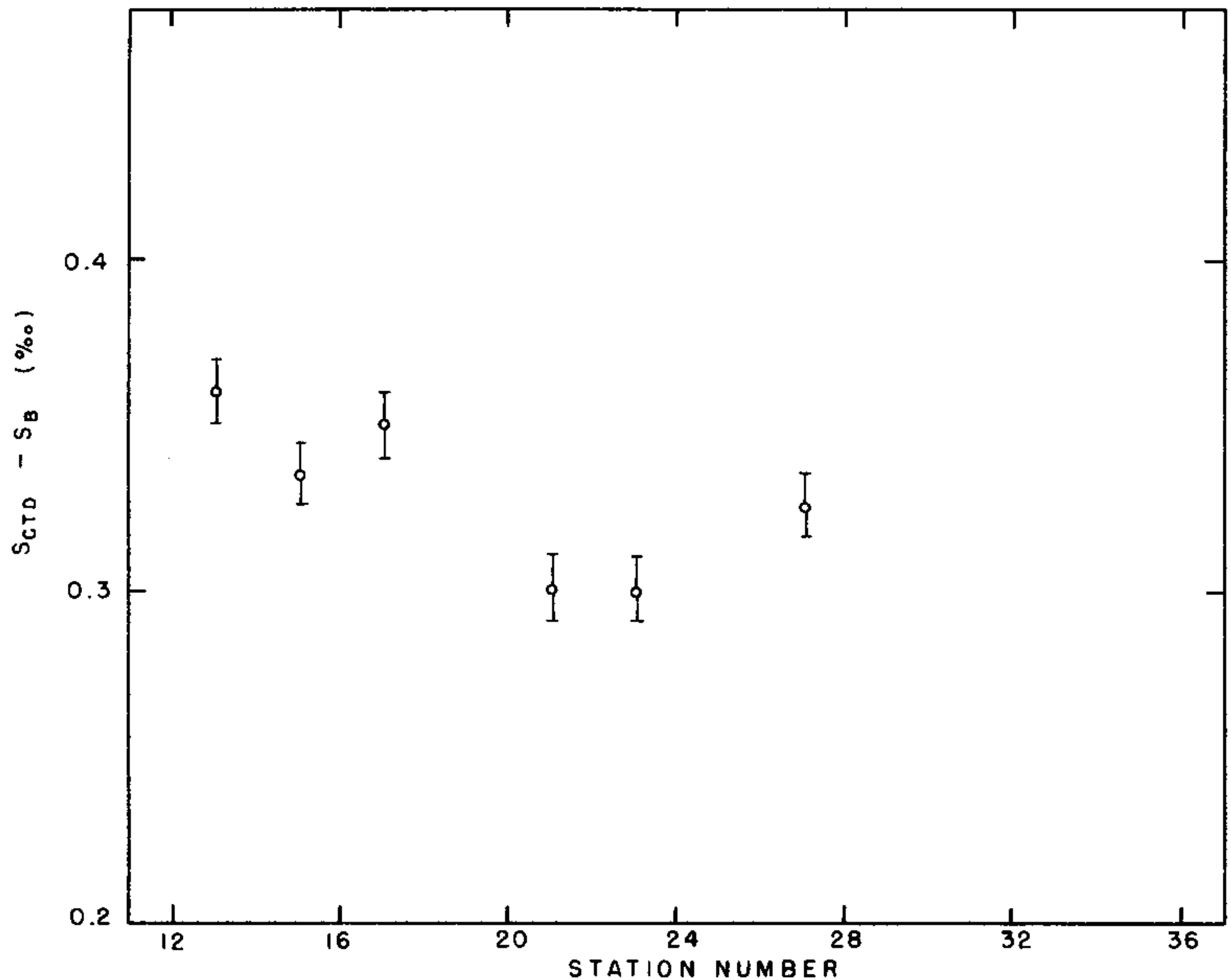

Figure 5: Difference of C.T.D. Reading from Bottle Reading (Bottom) vs Station Number. 5-6 May

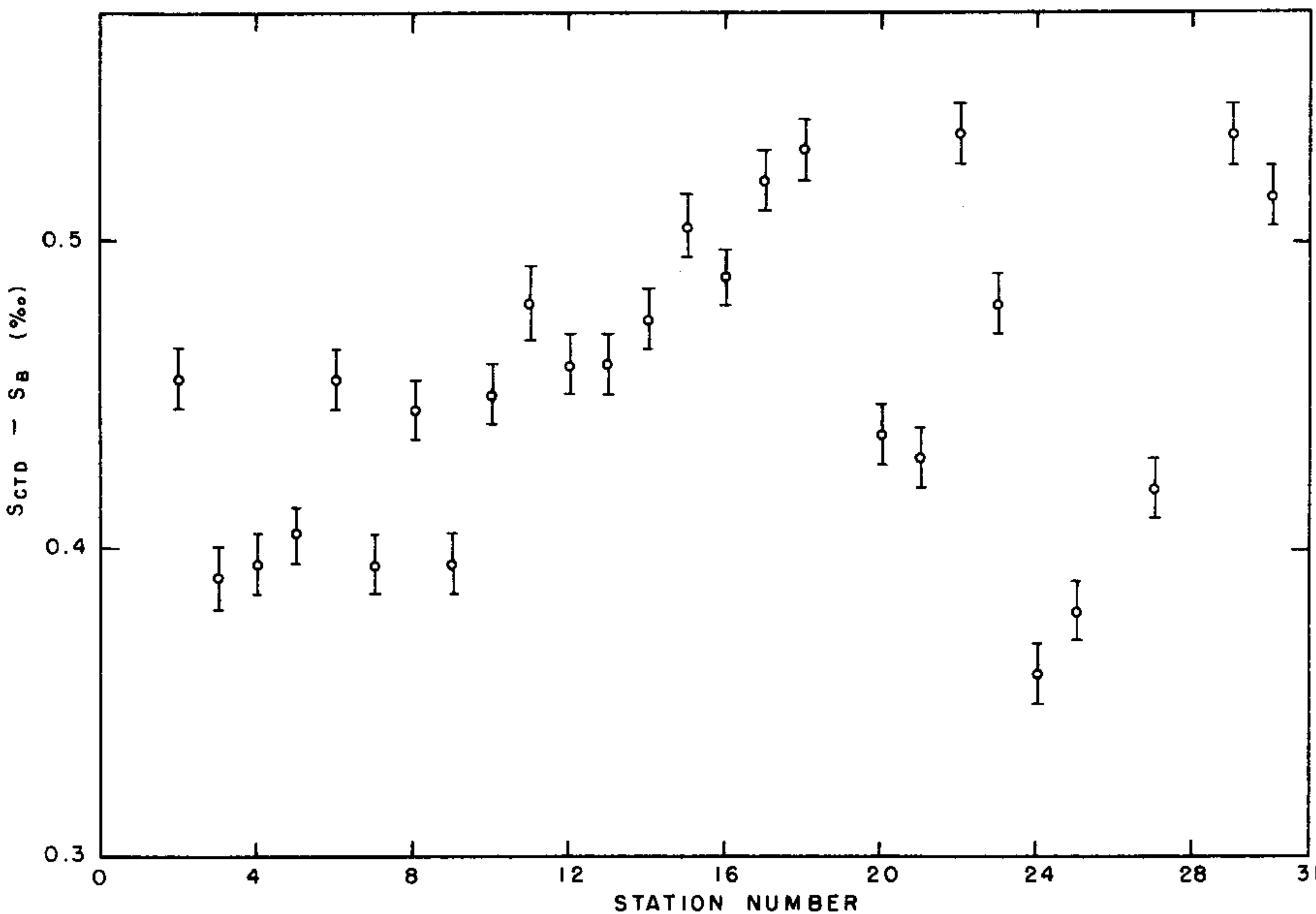

Figure 6: Difference of C.T.D. Reading from Bottle Reading vs Station Number. 2-3 June

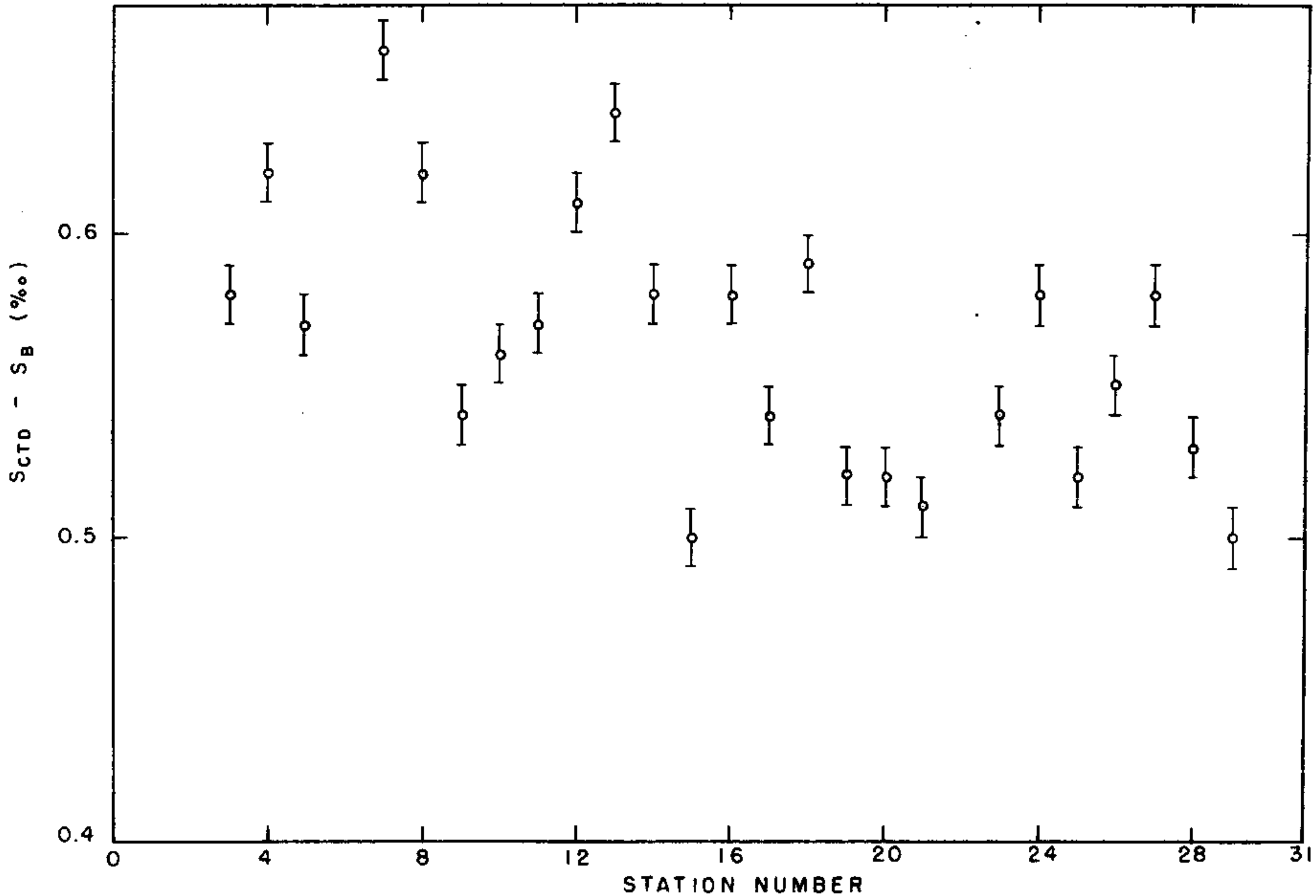

Figure 7: Difference of C.T.D. Reading from Bottle Reading vs Station Number. 13-14 June

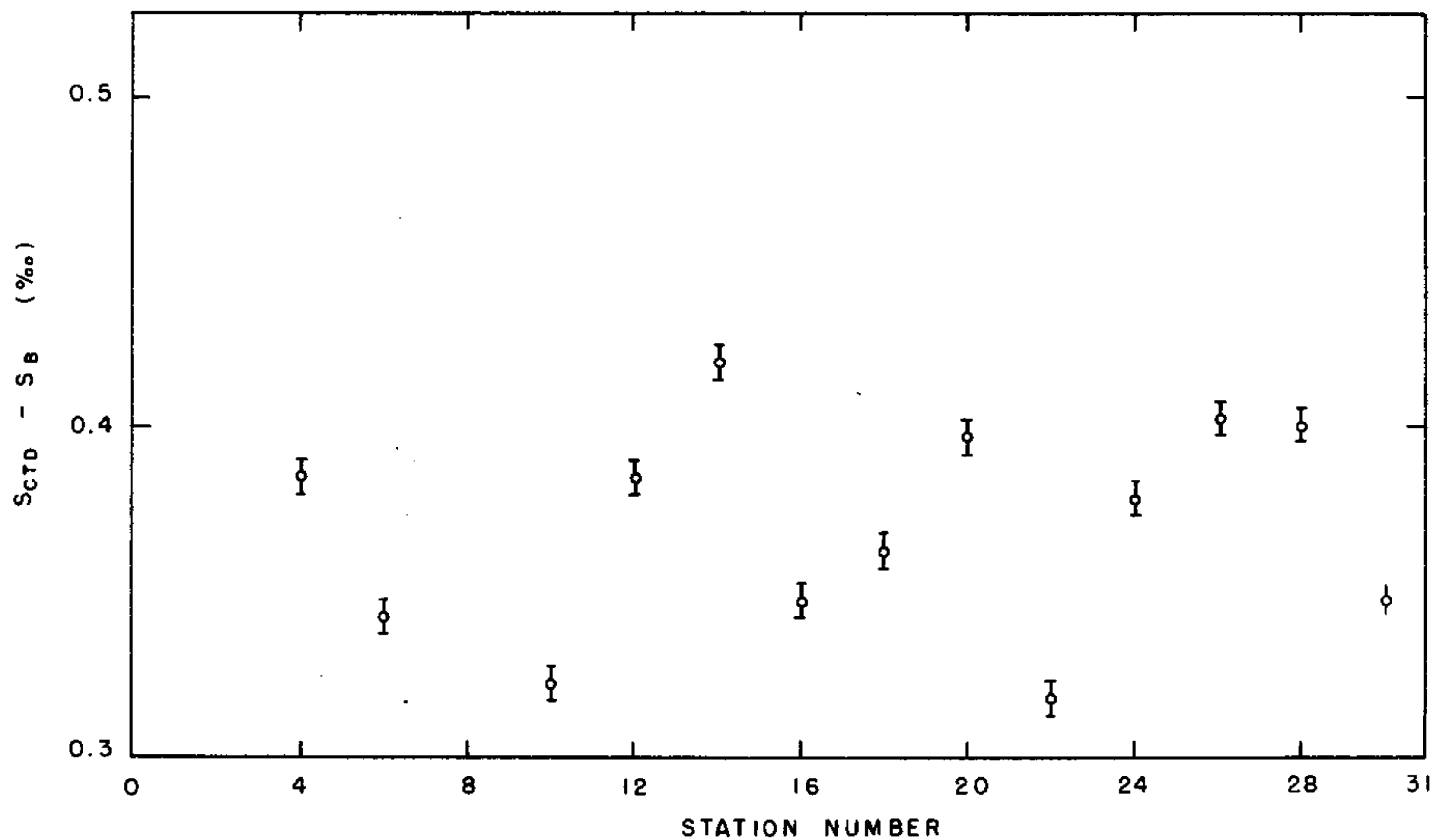

Figure 8: Difference of C.T.D. Reading from Bottle Reading (Bottom) vs Station Number. 13-14 June

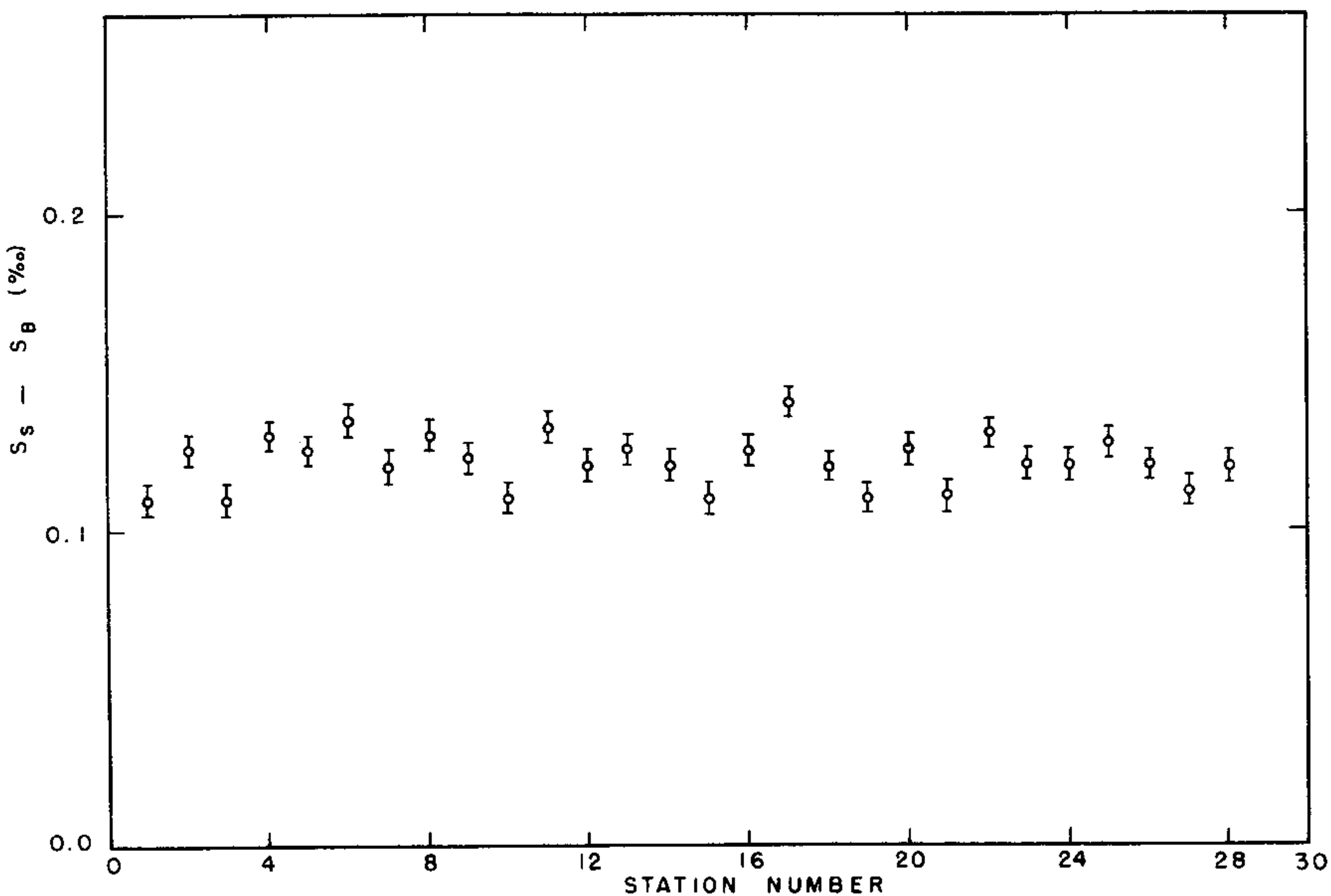

Figure 9: Difference of Salinograph Reading from Bottle Reading vs Station Number. 29-30 March

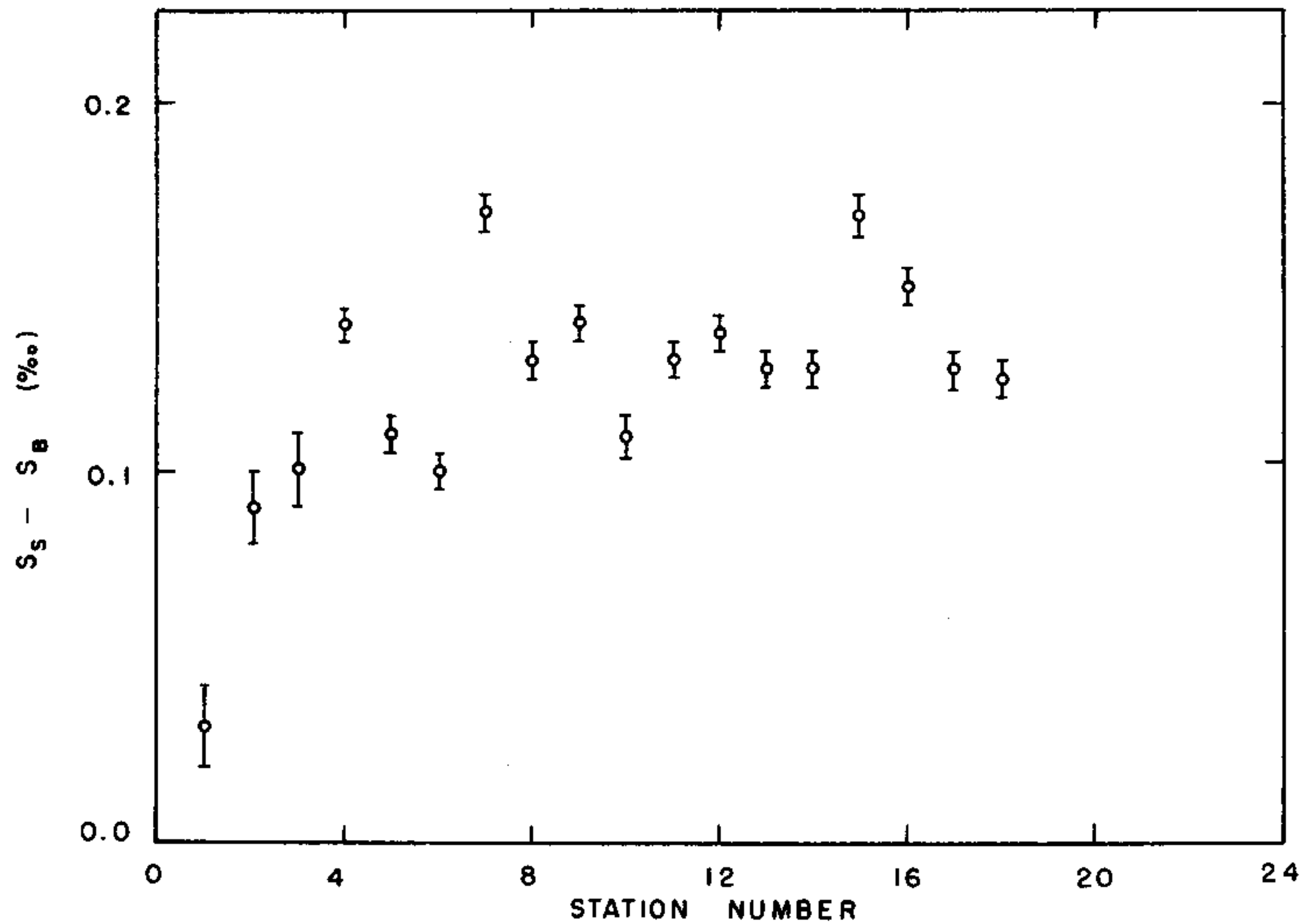

Figure 10: Difference of Salinograph Reading from Bottle Reading vs Station Number 14-15 April

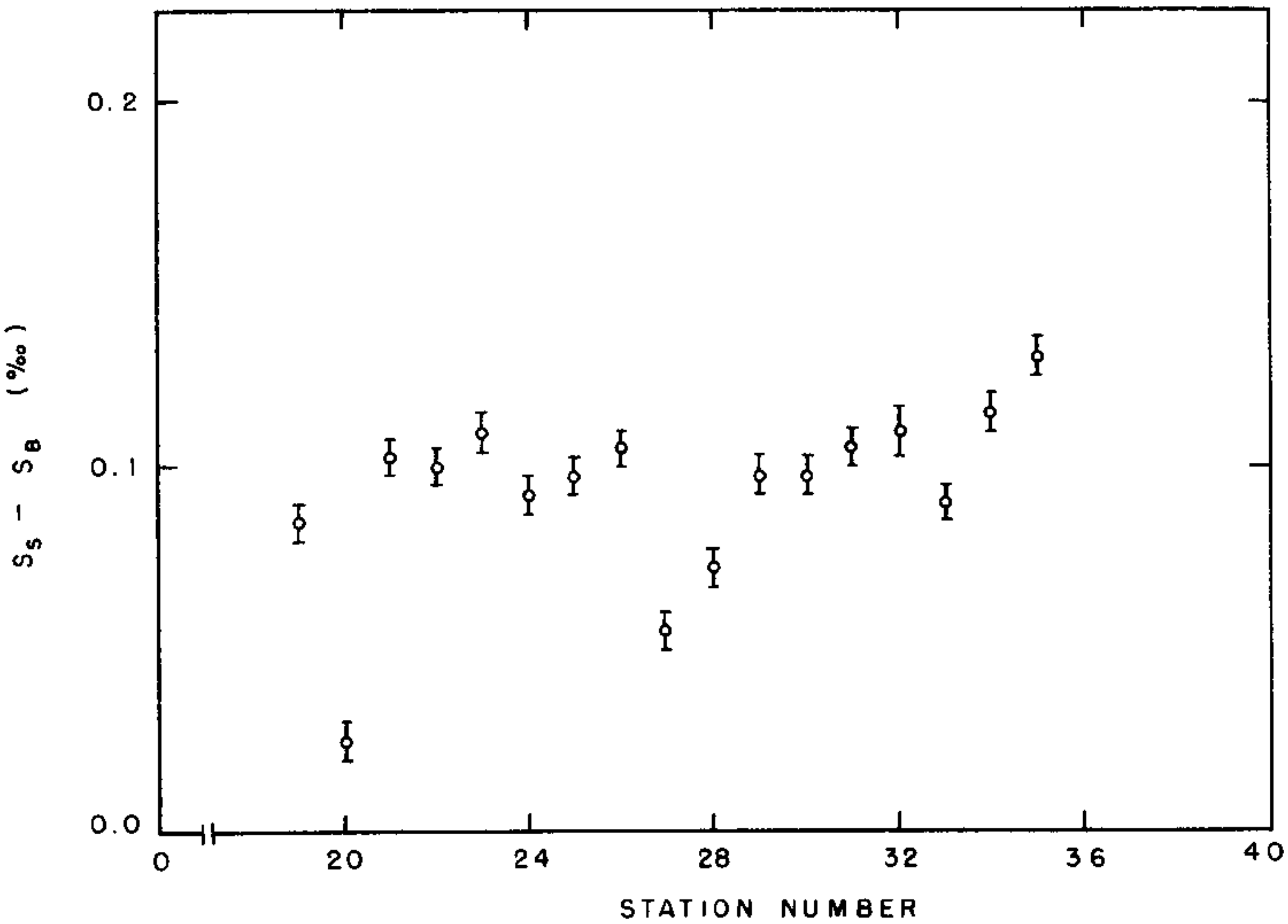

Figure 11: Difference of Salinograph Reading from Bottle Reading vs Station Number
21-22 April

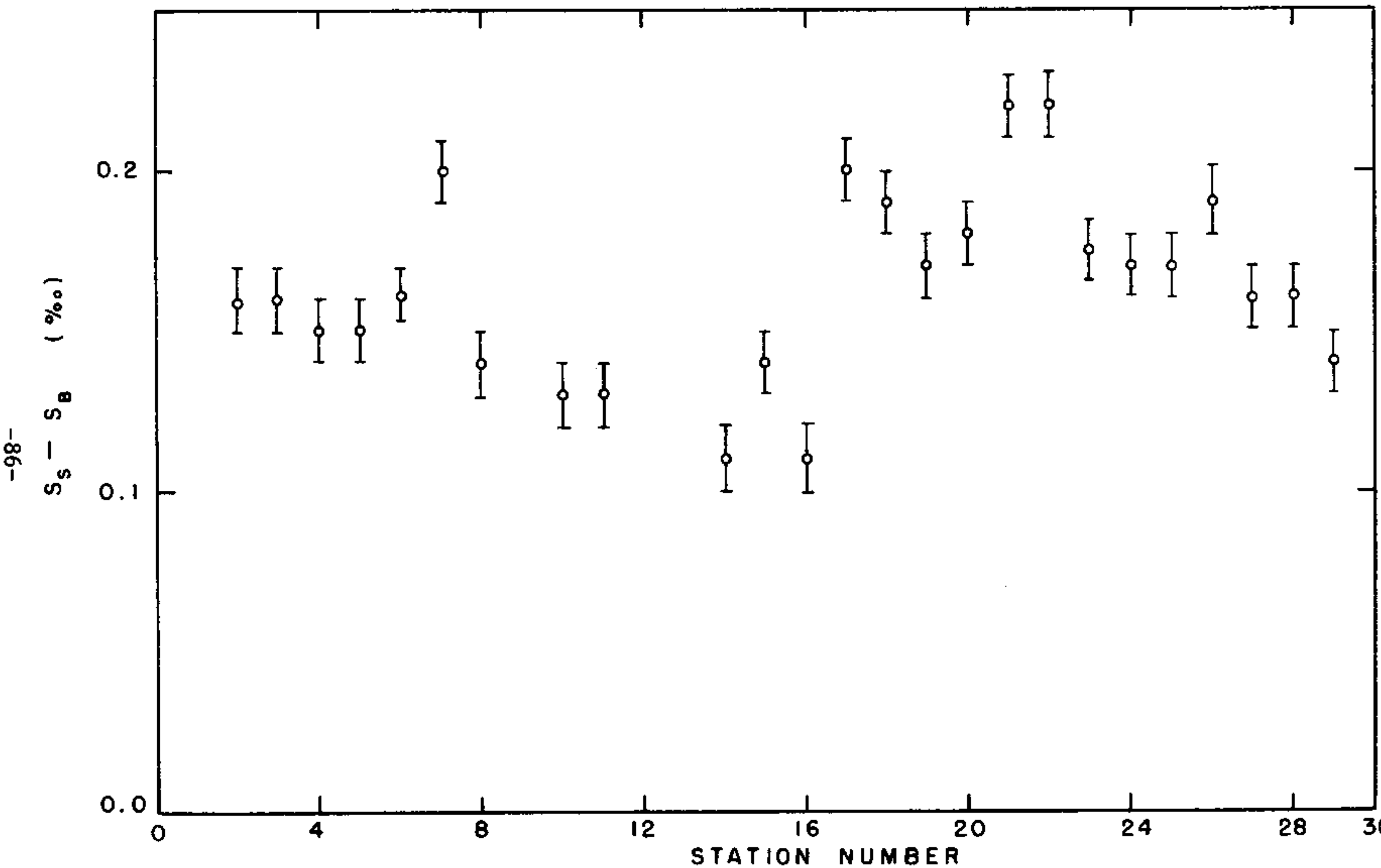

Figure 12: Difference of Salinograph Reading from Bottle Reading vs Station Number. 5-6 May

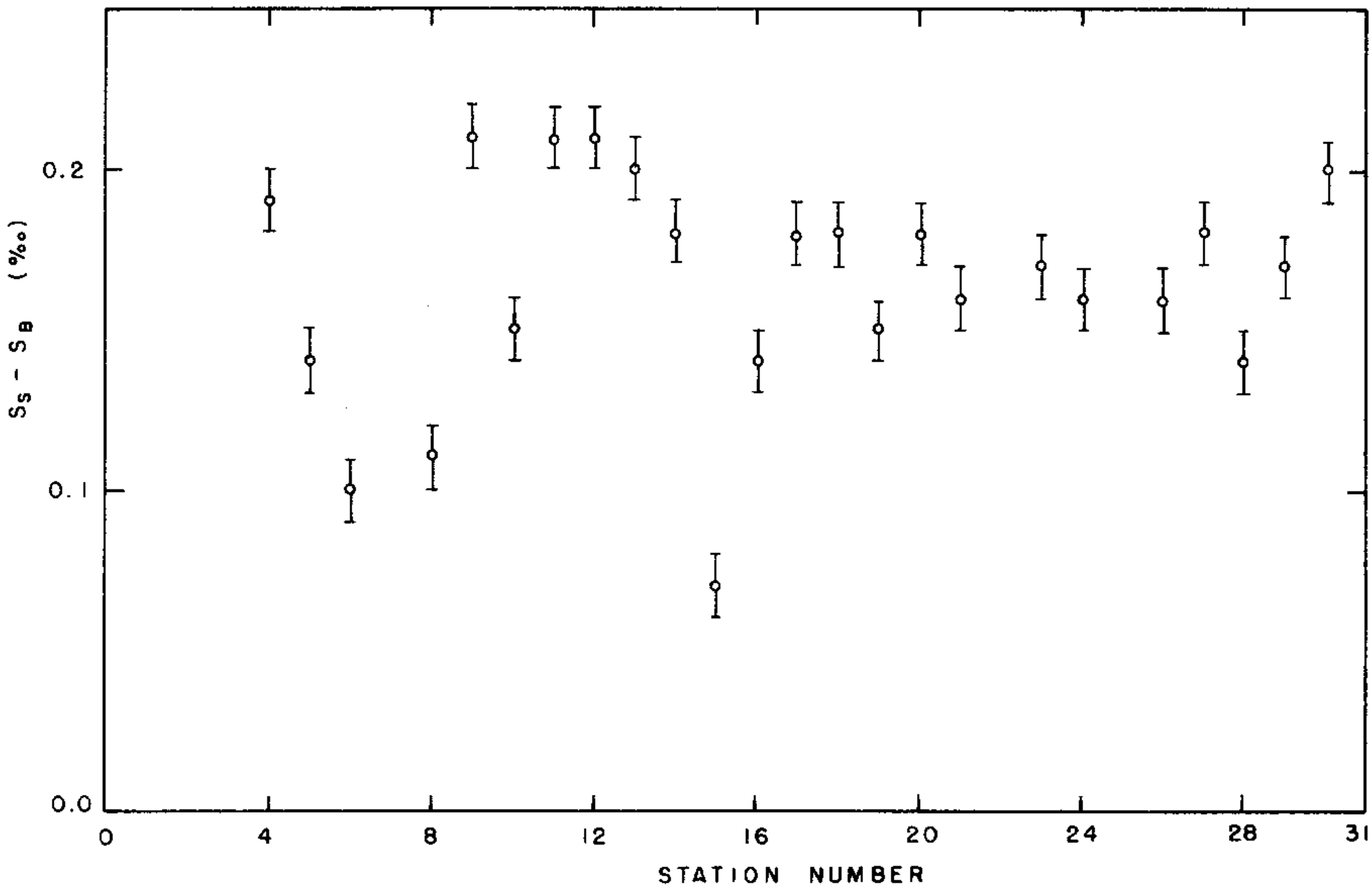

Figure 13: Difference of Salinograph Reading from Bottle Reading vs Station Number. 13-14 June

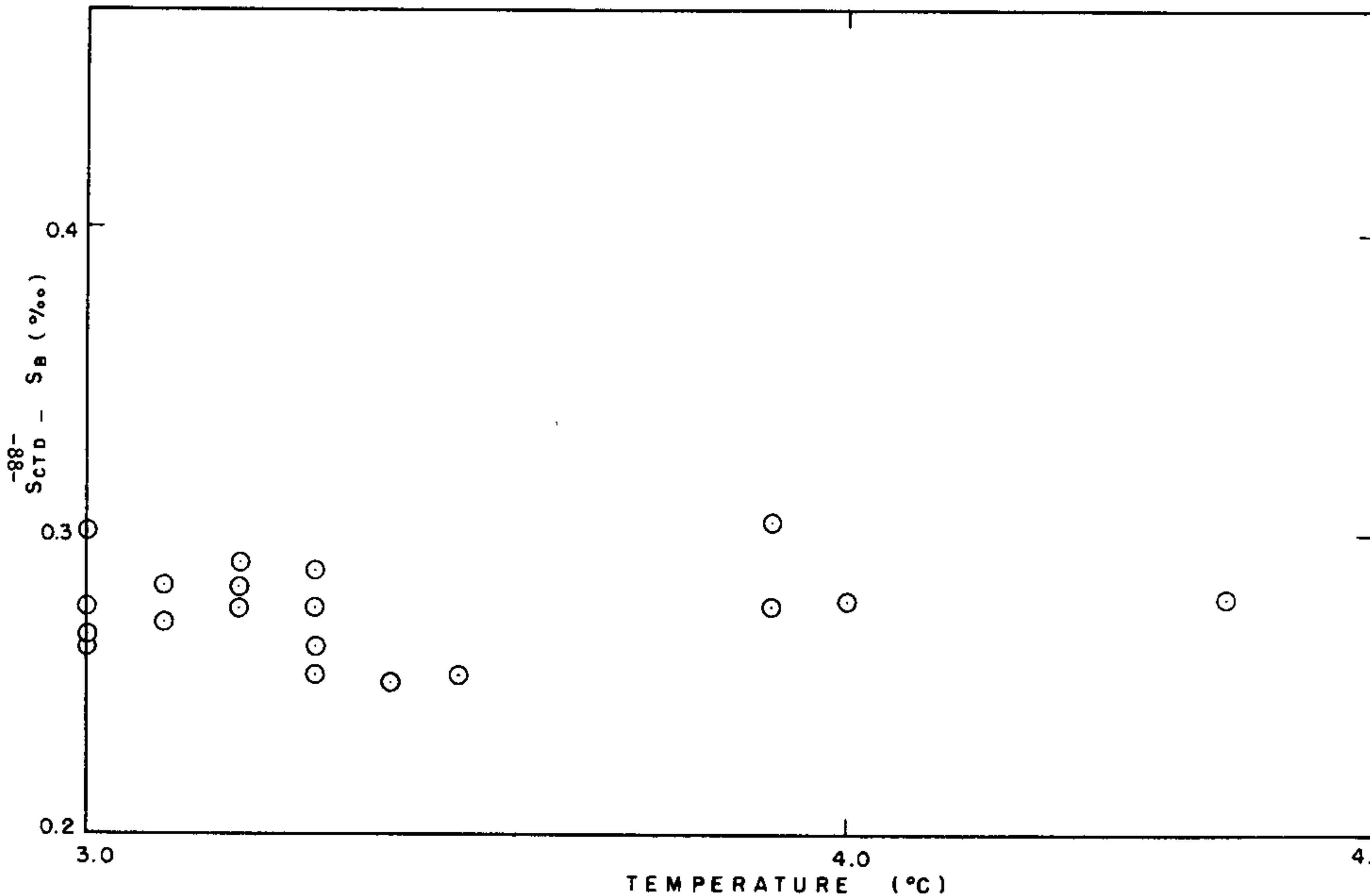

Figure 14: Difference of C.T.D. Reading from Bottle Reading vs in situ Temperature. 29-30 March

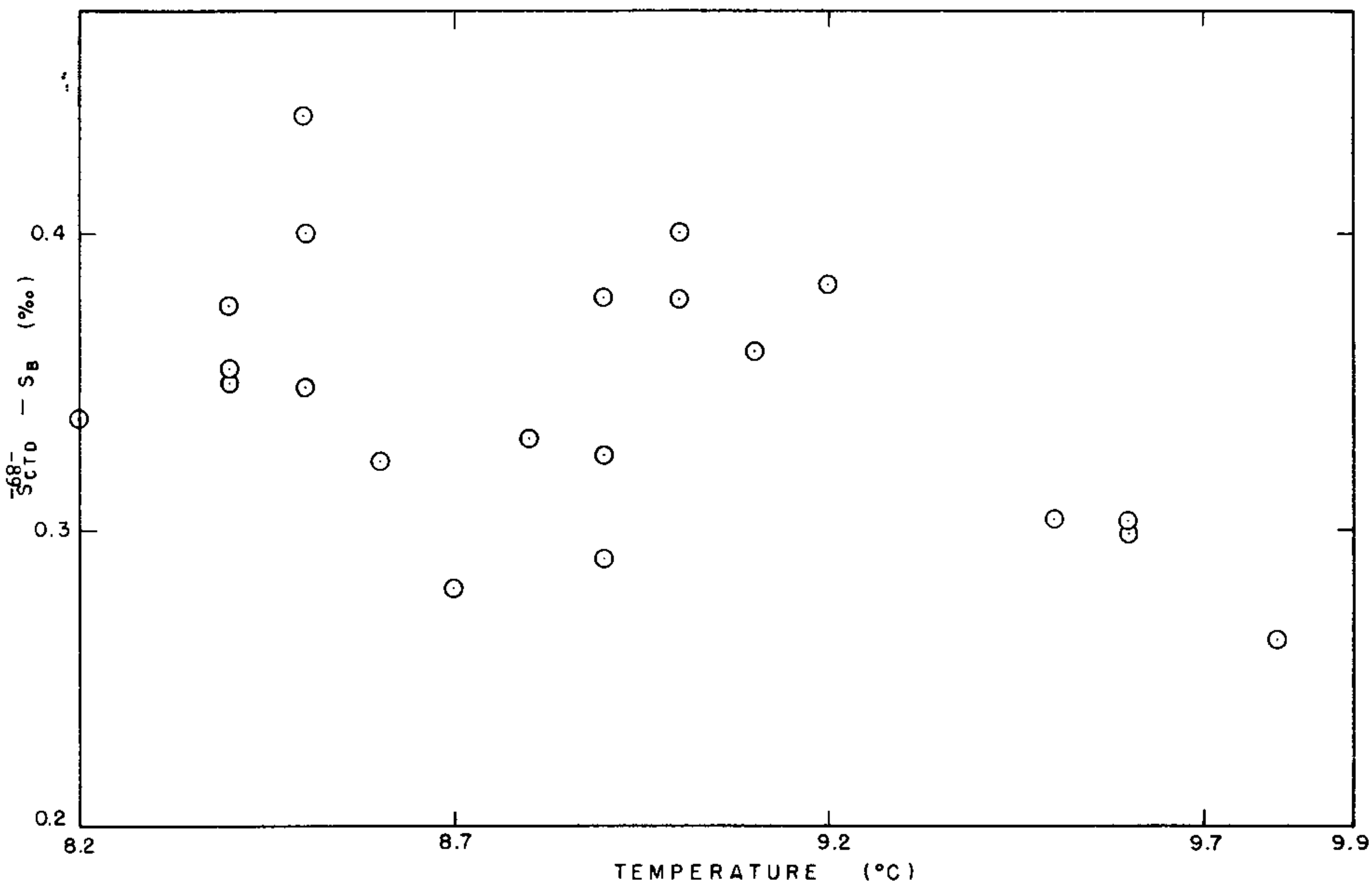

Figure 15: Difference of C.T.D. Reading from Bottle Reading vs in situ Temperature. 5-6 May

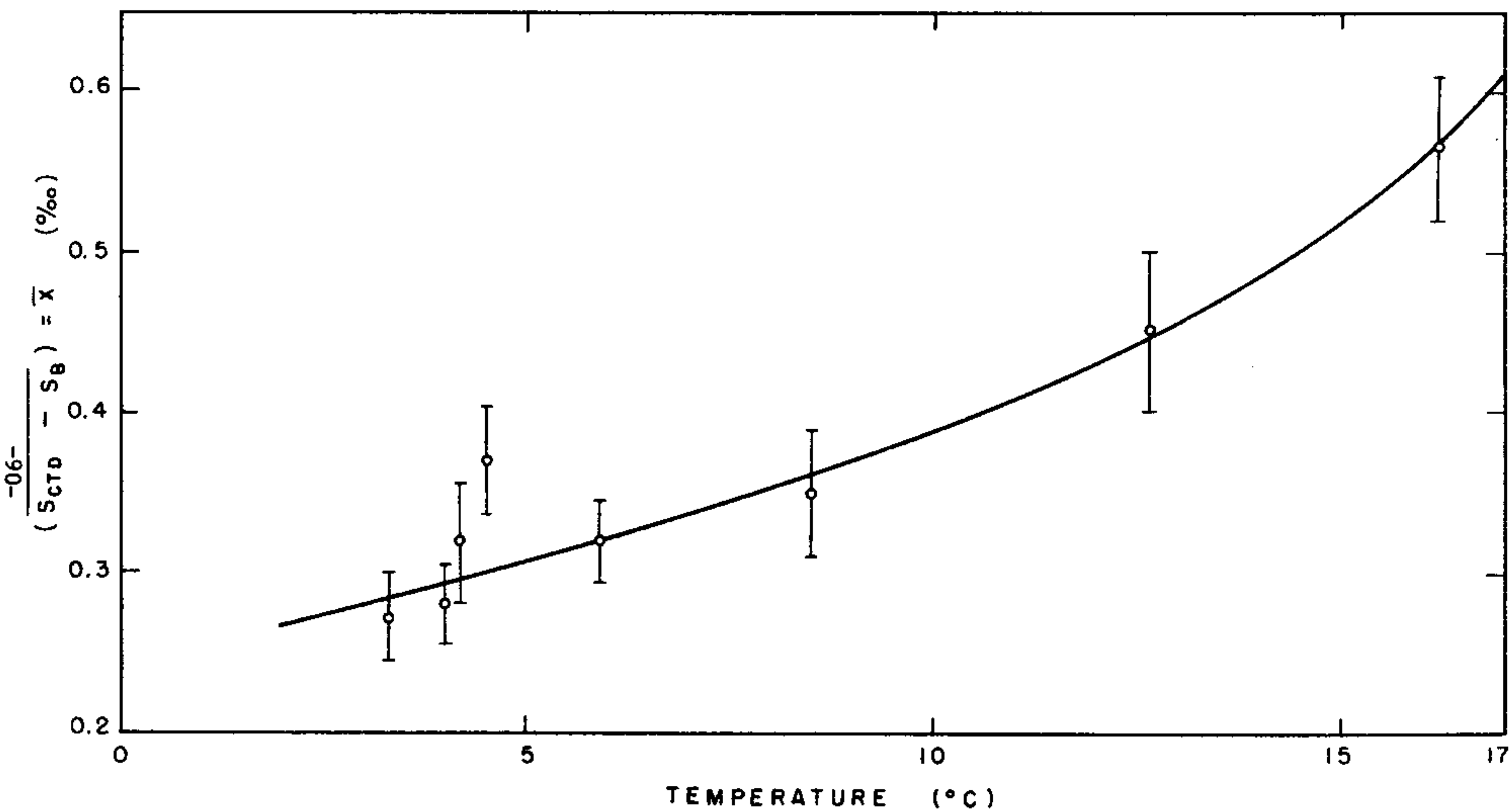

Figure 16: Mean Deviation of C.T.D. Reading from Bottle Reading vs Mean in situ Temperature

APPENDIX C

VERTICAL PROFILE OF SALINITY AND TEMPERATURE AT STATIONS 17, 11, 16 and 18

29-30 MARCH 1973

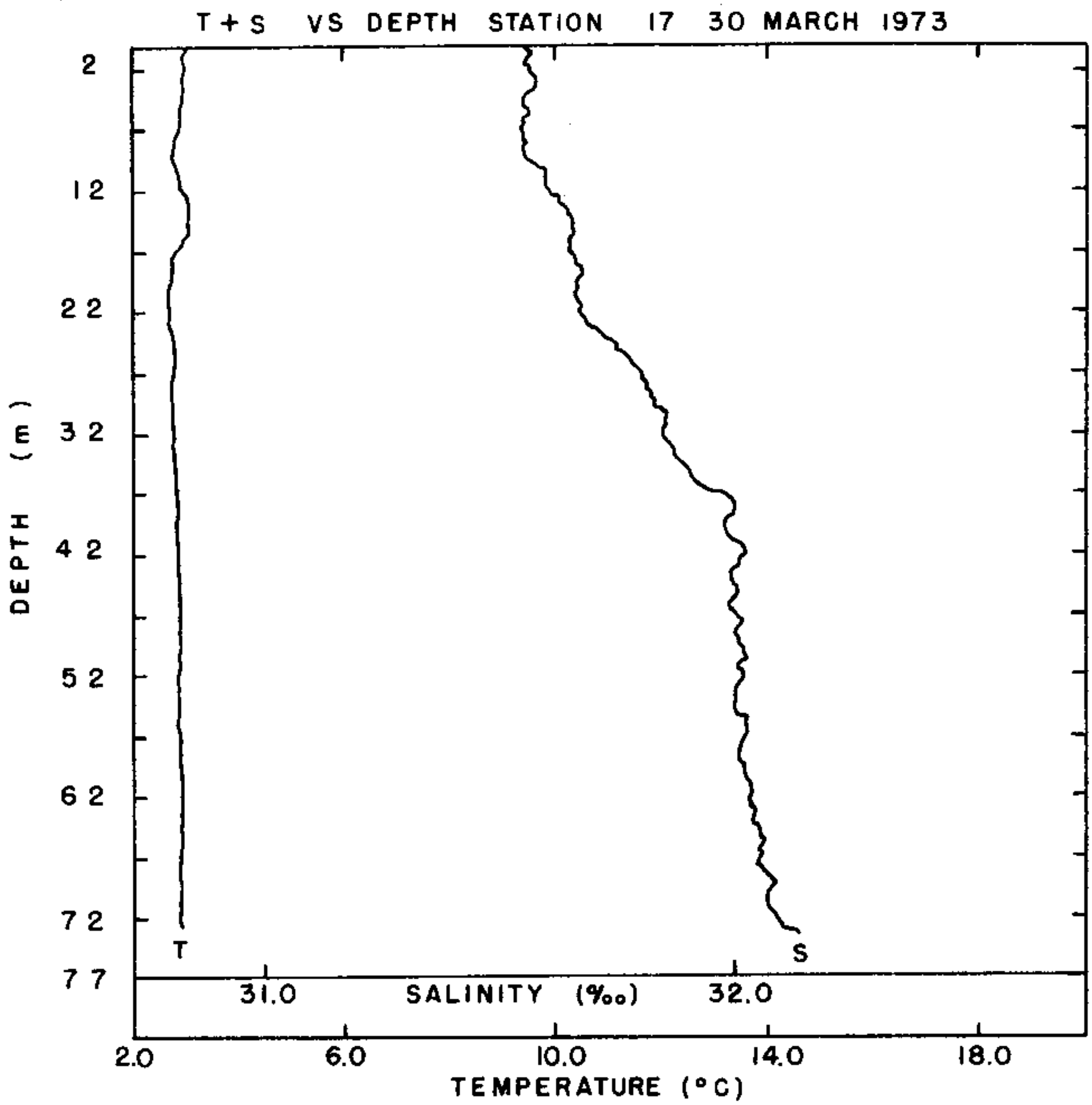

Figure 1: Salinity and Temperature vs Depth at Station 17, 29-30 March

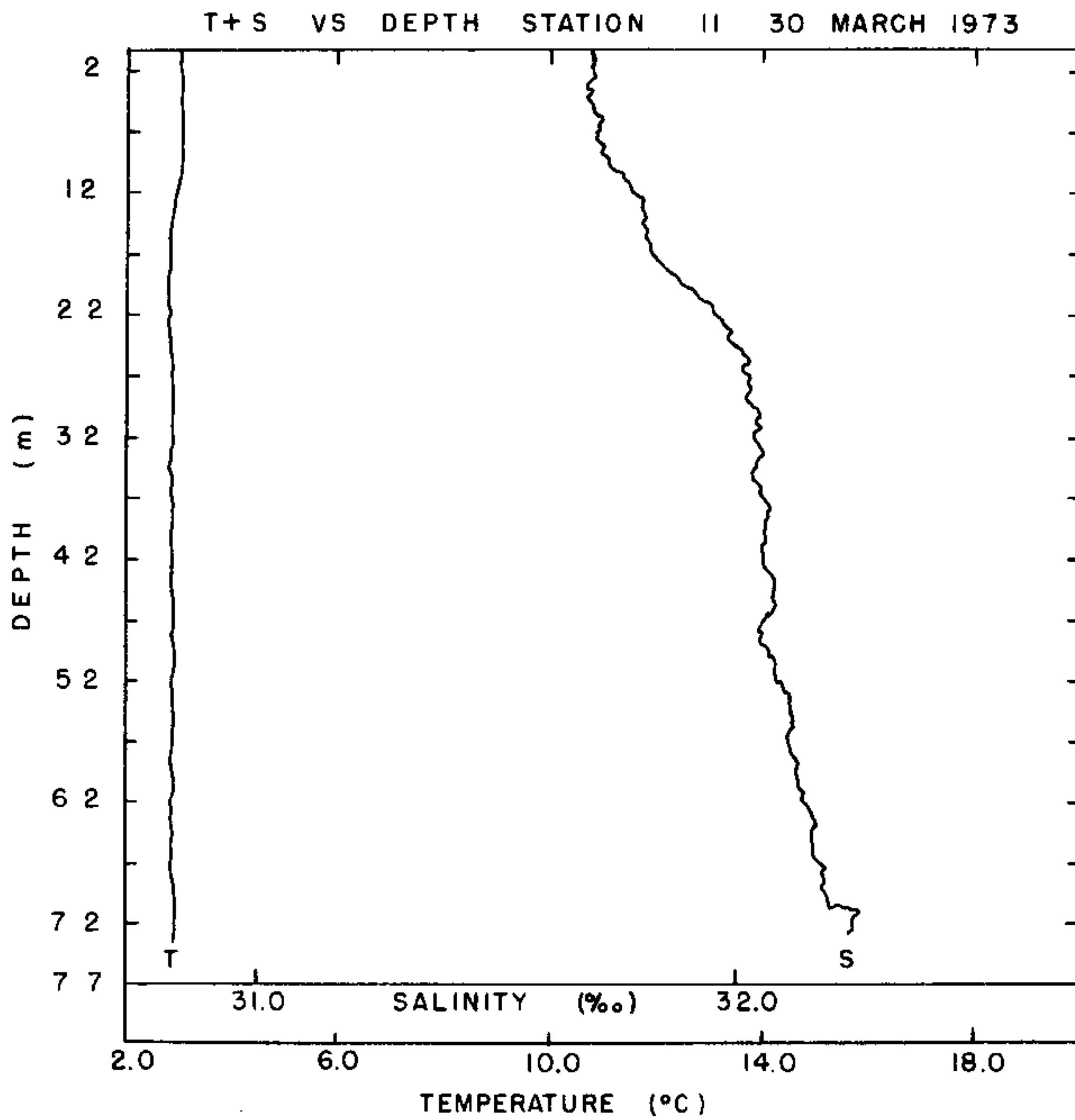

Figure 2: Salinity and Temperature vs Depth at Station 11, 29-30 March

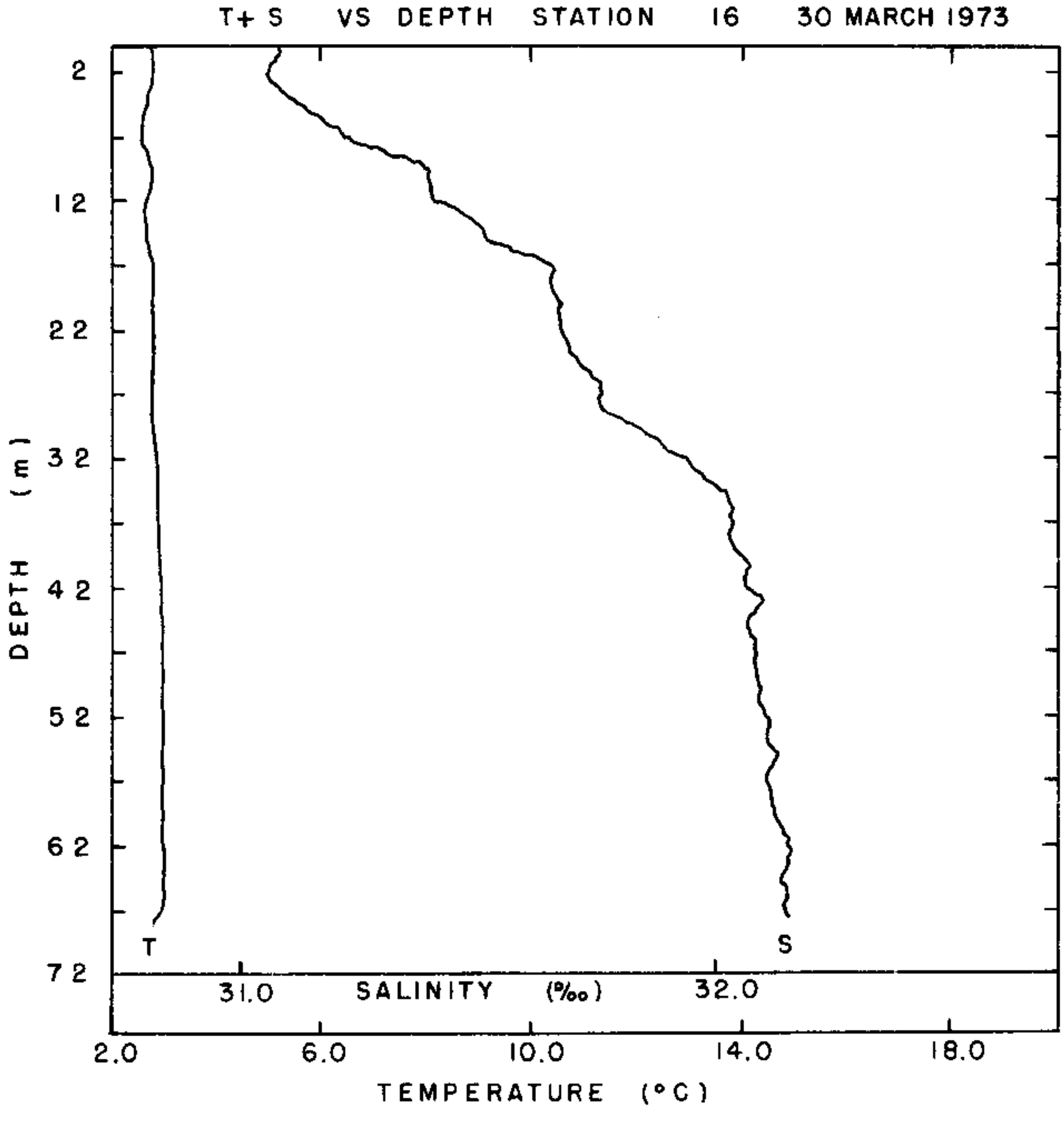

Figure 3: Salinity and Temperature vs Depth at Station 16, 29-30 March

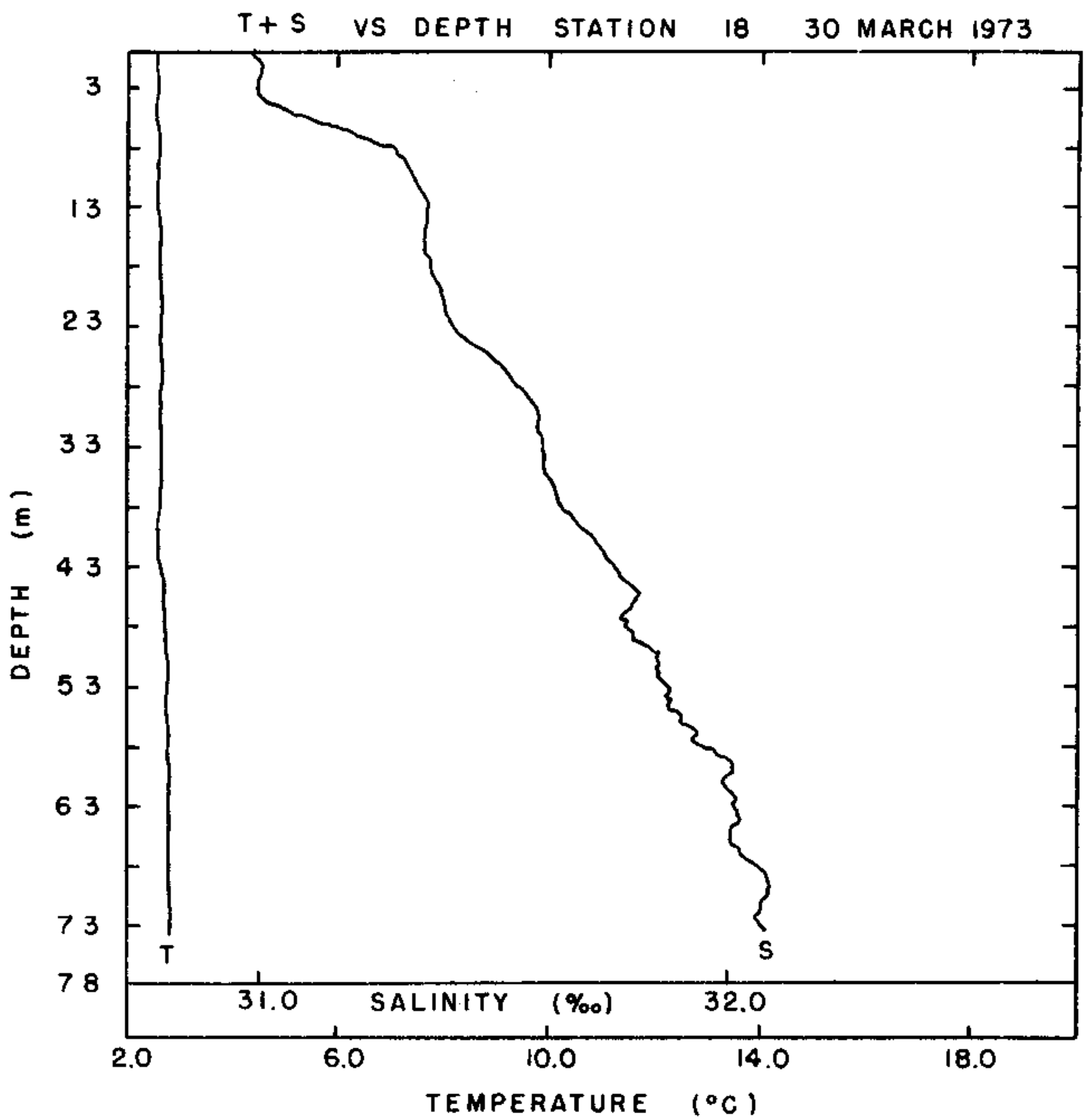

Figure 4: Salinity and Temperature vs Depth at Station 18, 29-30 March

APPENDIX D

DERIVATION OF FORMULAE

A. Determination of Fresh Water Volume

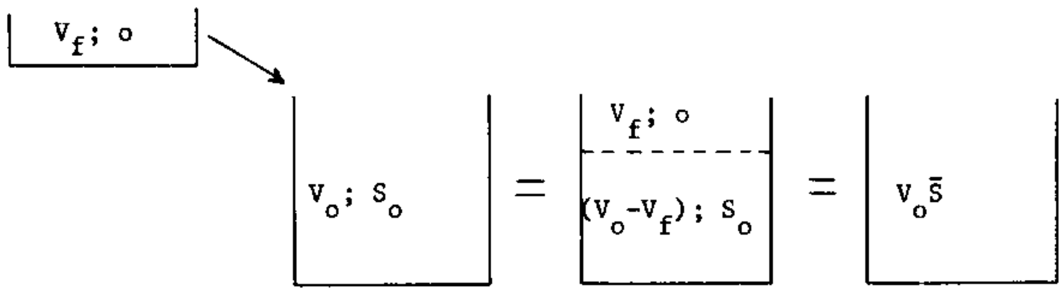

Figure 1

Let V_o and S_o represent the total volume and initial salinity of the Bay, respectively. Let V_f be the volume of fresh water added. This volume of fresh water displaces an equal volume of water of salinity S_o. Let $\bar{S}$ represent the average salinity in the Bay after the volume of fresh water V_f is added.

Since the total salt in the Bay, $V_o\bar{S}$, must equal the sum of that due to the fresh water, V_f, and that due to the remaining water of salinity S_o,

$$V_o\bar{S} = V_f \times 0 + (V_o - V_f)\, S_o .$$

This expression may be solved to yield the fraction of fresh water, f, as

$$f = \frac{V_f}{V_o} = \frac{S_o - \bar{S}}{S_o} .$$

B. Determination of Average Salinity, $\bar{S}$

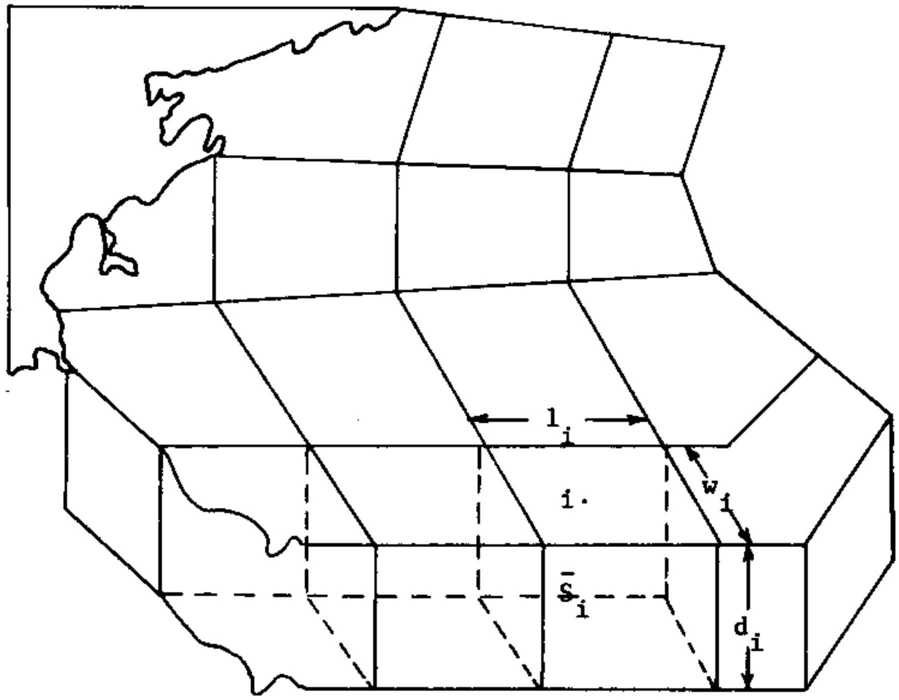

Figure 2

Now consider the Bay to be divided into rectangular boxes centred at each station, as shown in Fig. 2. Let l_i, w_i, d_i, and $\bar{S}_i$ represent the length, width, depth, and average salinity of the box at the i-th station. The depth averaged salinity $\bar{S}_i$ is defined by

$$\bar{S}_i = \frac{\sum_{j=1}^{d_i} S_{ij}\ \Delta d}{d_i}$$

where S_{ij} is the salinity for the i-th station at a depth of $(j-1)\Delta d$. The depth interval Δd is taken at 1 m.

Let $\bar{S}$ represent the average salinity of the bay (considered here to be the entire control volume), and V_o the volume of the bay. Then

$$V_o\bar{S} = \sum_{i=1}^{N} w_i l_i d_i \bar{S}_i,$$ where N is the number of stations and

$$V_o = \sum_{i=1}^{N} w_i l_i d_i$$

Since the spacing of the stations was approximately constant, w_i and l_i were taken to be constant, resulting in the simplified expression for the average salinity

$$\bar{S} = \frac{\left(\sum_{i=1}^{N} d_i \bar{S}_i\right)}{\sum_{i=1}^{N} d_i}$$

The calculation of $\bar{S}$ by this method would be in serious error if the average depth $\left(\frac{1}{N} \sum^{N} d_i\right)$ as determined by the casts was significantly different than the average depth of the bay. The average depth of the bay was determined independently using a much finer uniform grid mesh superimposed on the U.S. Coast and Geodetic Survey Navigation Chart #1207. It was found that the average depth as determined by the casts differed by less than 4% from the independently computed value.

C. Determination of Loss of Fresh Water Per Day

The method used for determining the volume of fresh water in the bay, Ketchum and Keen (1955), assumes that after the fresh water enters, the bay is mixed uniformly. This means that the water in the bay and the adjacent sea is as shown in Fig. 3.

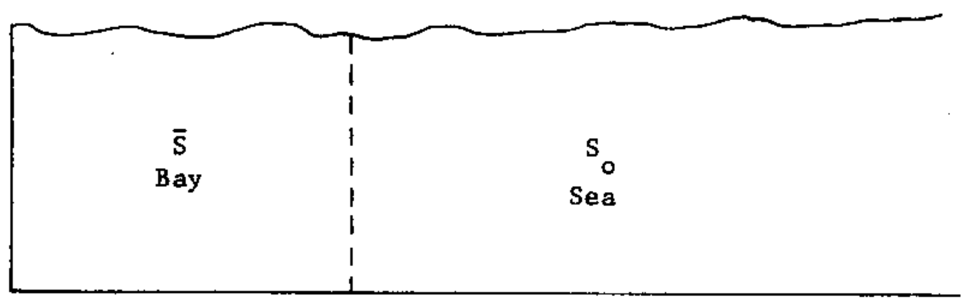

Figure 3

The bay contains homogeneous water of salinity $\bar{S}$, and the region adjacent to the bay is homogeneous with salinity S_o. We assume that the rate of diffusion of salt, $\frac{d(\bar{S}V_o)}{dt}$, into the bay is proportional to the salinity difference between the open sea and the bay water, i.e.,

$$\frac{d(\bar{S}V_o)}{dt} = k(S_o - \bar{S})$$

where k is taken to be constant.

Since $\bar{S}V_o = (V_o - V_f)S_o$, we see that the rate of loss of freshwater from the bay $\frac{dV_f}{dt}$, is proportional to the amount of freshwater present, i.e.,

$$\frac{d(\bar{S}V_o)}{dt} = - S_o \frac{dV_f}{dt} = k(S_o - \bar{S}) = \frac{kS_o}{V_o} V_f,$$

or

$$\frac{dV_f}{dt} = -\frac{k}{V_o} V_f.$$

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SPRING RUN-OFF AND NUTRIENT-SEAWATER DENSITY CORRELATIONS IN THE MASSACHUSETTS BAY

PART II. DISSOLVED NUTRIENT-SEAWATER DENSITY CORRELATIONS AND THE CIRCULATION IN BOSTON HARBOR AND VICINITY

by

Joseph Karpen

SPRING RUN-OFF AND NUTRIENT-SEAWATER DENSITY CORRELATIONS IN THE MASSACHUSETTS BAY

ABSTRACT - PART II

DISSOLVED NUTRIENT-SEAWATER DENSITY CORRELATIONS AND THE CIRCULATION IN BOSTON HARBOR AND VICINITY

BY

JOSEPH KARPEN

The general circulation between Boston Harbor and Massachusetts Bay was studied from the basis of a tidal exchange problem. The Deer Island Sewage Treatment Plant effluent outfall, located at the mouth of the harbor, was used as a tracer of harbor water.

An exchange theory using simplified jet and sink flows was developed to predict the effluent concentrations in the harbor. A correlation between dissolved nutrient concentrations and sigma-t (density) was postulated.

Five cruises were undertaken to verify the theory presented: hydrographic stations were made using a Conductivity-Temperature-Depth (CTD) sensor package, and water samples were taken to measure dissolved nutrient concentrations. Wind induced surface and possible geostrophic currents were noted as other sources of flow.

A significant correlation was found between dissolved nutrient concentrations and sigma-t. It appears the harbor water mass moves seaward into Massachusetts Bay as a large, fairly homogenous volume, "blob", a new blob moving into the Bay on each ebb tide. Further avenues of study are mentioned, especially with respect to the movement of the harbor water into the Bay.

PART II

ACKNOWLEDGEMENTS

This study constitutes a part of a series of investigations in a major environmental research program on the "Sea Environment in Massachusetts Bay and Adjacent Waters". This program consists of theoretical and field investigations and is under the administrative and technical direction of Dr. Arthur T. Ippen, Institute Professor, Department of Civil Engineering and of Dr. Erik L. Mollo-Christensen, Professor, Department of Meteorology as co-principal investigators. Support of the program is provided in part by the Sea Grant Office of NOAA, Department of Commerce, Washington, D.C. through Grant No. NG-43-72, in part by the Henry L. and Grace Doherty Charitable Foundation, Inc., and in part by the Department of Natural Resources, Commonwealth of Massachusetts through Project No. DMR-73-1. The project which is the subject of this report was conducted by the author while a research assistant in the Department of Meteorology and was administered under Project Nos. 80344 and 80345.

Acknowledgement is here expressed to Dr. E.L. Mollo-Christensen, Professor of Meteorology, and Dr. Robert C. Beardsley, Associate Professor of Meteorology, who acted as project supervisors. Helpful suggestions were made by Professor Henry M. Stommel and Dr. P. Rhines. Mr. B. Laird assisted with the computer programming. Messrs. K. Kim, D. Strimaitas and E. Sambuco acted as crew members on the data collection cruises. Ms. S. Frankel aided with the chemical determinations.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF SYMBOLS

Symbol	Definition	Dimensions
b	Half width of an opening	L
C, C(I), C_s	A concentration of dissolved nutrients or pollutants	-
d	Depth of upper mixed layer	L
D	Diffusivity of dissolved nutrients	L^2/T
E	Dissolved nutrient or pollutant flux (a concentration times a volume flux)	L^3/T
K, K'	Integration constants	-
Q	Flux through harbor opening	L^3/T
Q'	Two dimensional flux through harbor opening	L^2/T
r	Radial distance from harbor opening	L
r_{xy}	Sample correlation coefficient	-
R1	Extent of sink flow region	L
R2	Length of tidal excursion	L
t	Time	T
t1	Time of half a tidal period	T
u	Velocity	L/T
Uo	Half tidal cycle average velocity	L/T
Vo	Wind induced surface current velocity	L/T
V1, V2, V3, V4, V5	Tidal exchange volumes, see Figure 4	L^3
w	Wind velocity	L/T
x	Measured value of Concentration	-

$\hat{x}$	Predicted value of concentration	-
y	Measured value of sigma-t	-
α	Probability of accepting a false hypothesis	-
δ	Anomaly of specific volume	L^3/M
Θ	Angle of opening	-
ρ_1, ρ_2	Density	M/L^3
ρ_{xy}	Correlation coefficient	-
$\tau_{e.f.}$	e-folding time (tidal cycles)	-
$\tau(I)$	Tidal period number	-
ϕ	Latitude	-

CHAPTER 1

INTRODUCTION

From the history of man, main areas of civilization have developed along coasts and on rivers. The local waters were used as convenient waste disposal areas; when populations were small, there was no noticeable effect on the quality of the local waters. The process of urbanization and industrialization has led to the development of large population centers along the coastlines, and the continued disposal of wastes in the local waters. As a result of this concentration of wastes in the near shore areas, they have become the "septic tank of the megalopis" (DeFalco, 1967). A report by Hydroscience, Inc. (1971) on the quality of the waters in Boston Harbor indicates the particularly poor situation that existed there prior to 1968 when the Deer Island Sewage Treatment Plant went into full operations.

Increasing population pressures make it necessary that a continuint study be done of the physical factors involved in coastal processes, to prevent pollution of our coastal zones. Of extreme importance is the circulation of the coastal waters and their movement of the waste materials of man from the coast out to sea.

Taylor's (1960) theory of diffusion by continuous movements formed the basis for the early work in dispersion of pollutants in water. The concept of tidal prisms was used by Ketchum (1951) to calculate the mixing of salt and fresh waters in tidal estuaries. Aarons and Stommel (1951) refined Ketchum's discrete tidal prisms into a continuous form.

A similarity solution for estuarine circulation was developed by Rattray and Hansen (1962). Bowden (1967) presents an overview of work done to that time, with emphasis on vertical and longitudinal circulation. A review of estuarine modeling by Overland (1972) covers advances from 1967 to 1972, and also includes an estuarine type classification system. Stommel and Farmer (1952) and Pritchard (1967) have given similar estuarine classifications.

Fischer (1972) includes transverse transport in his model for mass transport in estuaries. He presents the idea "that a net transverce circulation may be induced by the interaction of tidal currents with the boundary geometry. The simplest example would be a flow through a small entrance into a circular basin, the flow enters as a jet and leaves as a potential sink, implying a net circulation inward along the diameter and outward along the edges". Stommel (1972) suggests this model might also fit the circulation between Boston Harbor and Massachusetts Bay; the water enters Massachusetts Bay as a jet (ebb tide), and on the flood tide flows into the harbor as a potential sink.

A simple theory for the dispersion of a source located at the mouth of Boston Harbor using jet and sink flow is developed in the following sections. Field work was undertaken to 1) determine the actual distribution of a source of dissolved nutrients (the Deer Island Treatment Plant effluent), 2) verify the dispersion theory and 3) determine if it is feasible to specify what the dissolved nutrient distribution should be by measuring the density distribution.

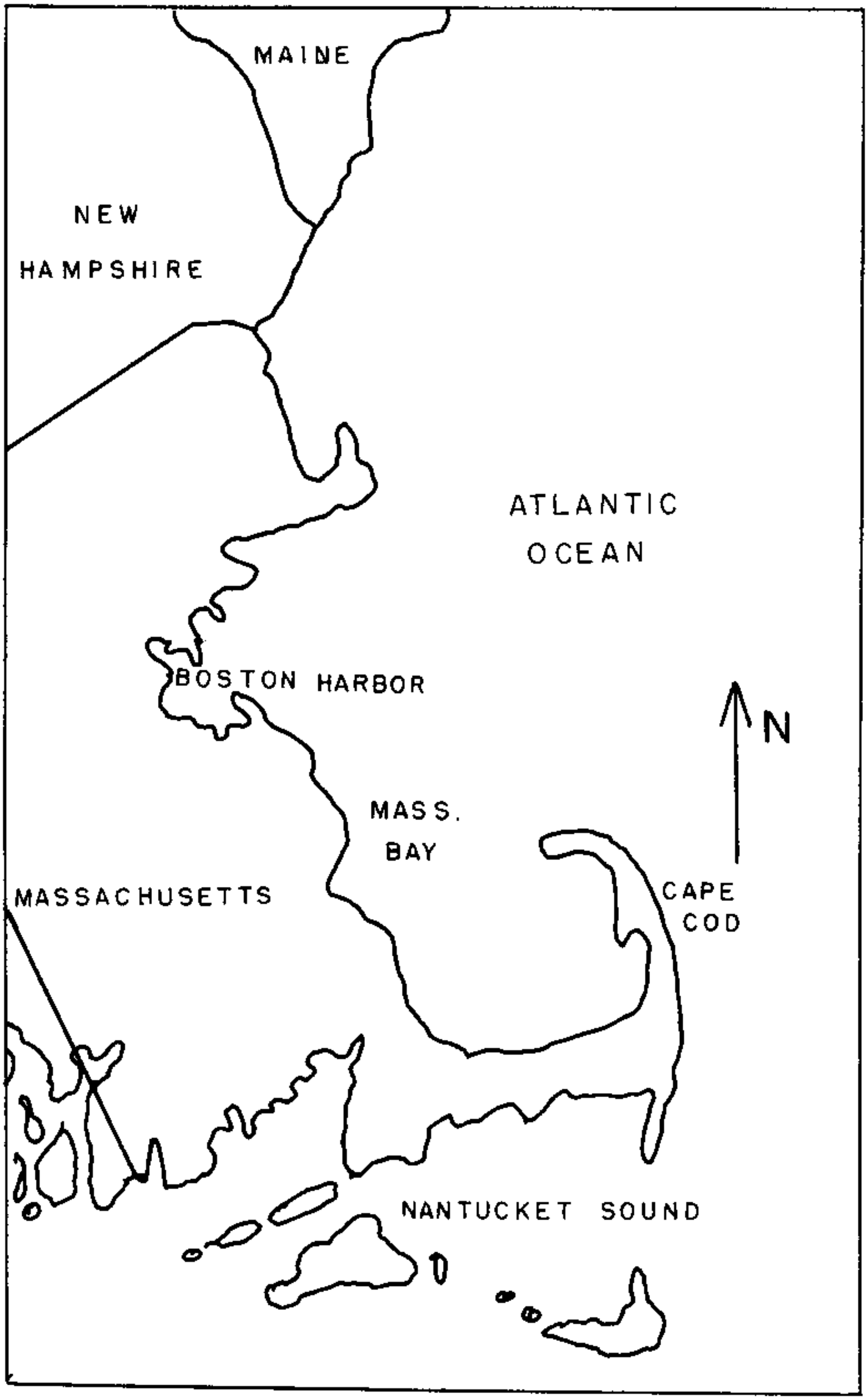

Figure I AREA MAP

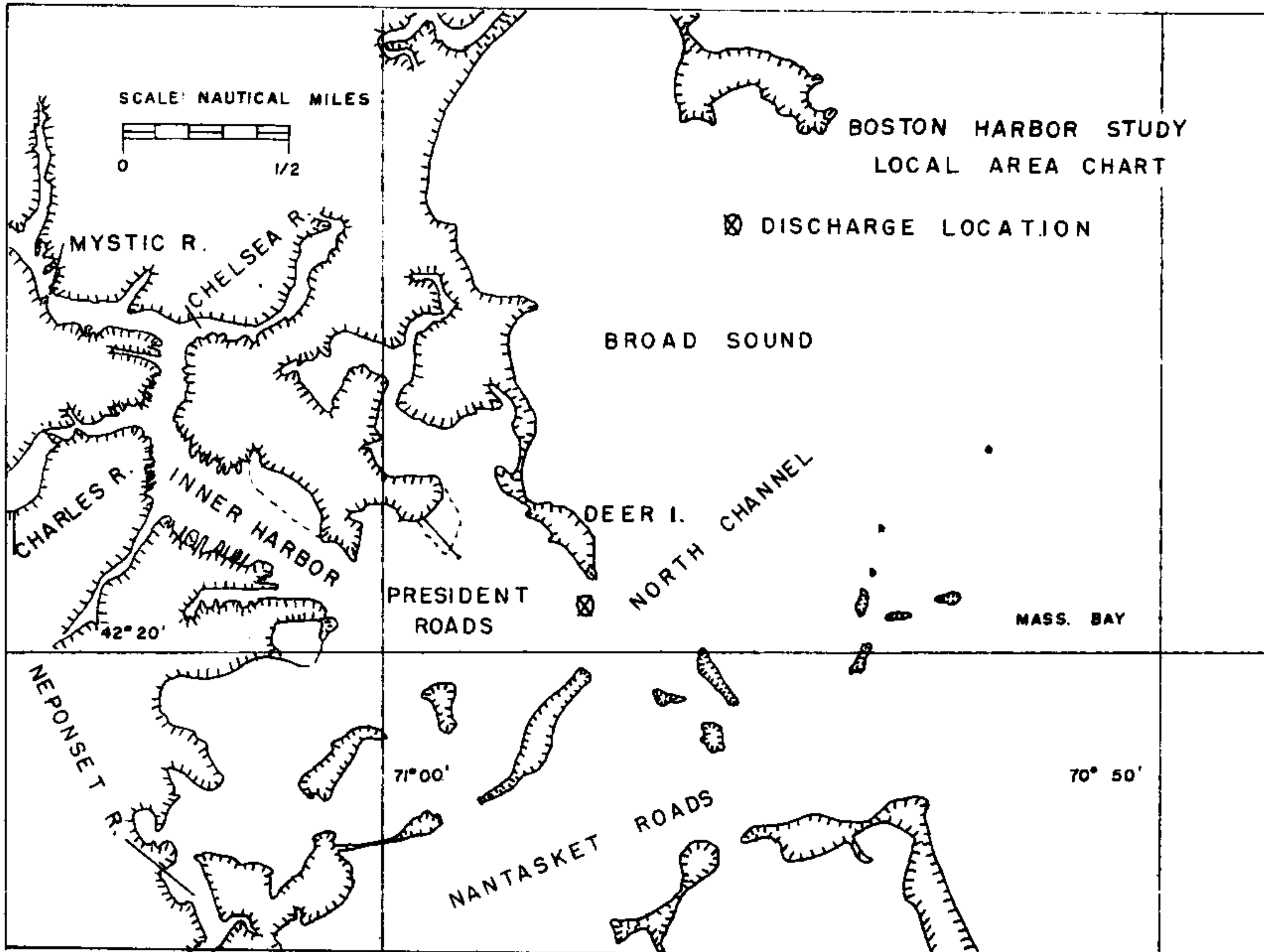
BOSTON HARBOR STUDY
LOCAL AREA CHART
DISCHARGE LOCATION
SCALE: NAUTICAL MILES
0
1/2
MYSTIC R.
CHELSEA R.
CHARLES R.
INNER HARBOR
BROAD SOUND
DEER I.
NORTH CHANNEL
PRESIDENT ROADS
MASS. BAY
42° 20'
71°00'
70° 50'
NEPONSET R.
NANTASKET ROADS

Figure 2

CHAPTER 2

THEORY

2.1 Preliminary

The area of study is Boston Harbor and the area of Massachusetts Bay adjacent to the harbor (Figure 1). The Deer Island Treatment Plant outfall, the source of dissolved nutrients to be used to study the harbor circulation, is located at the mouth of the harbor, just east of President Roads (Figure 2). The effluent is assumed to rise to the surface, where it then mixes with the harbor water to a depth of three to four meters. On this basis, the flow theory to be developed will be based on two dimensional jet and sink theory.

The ebb tidal flow into the Bay is assumed to be a jet, the flood tidal flow from the Bay is a potential sink. Conversely, the ebb tidal flow from the harbor is assumed to be a potential sink, and the flood tidal flow is a jet into the harbor. Coriolis effects are neglected, and the time scale for significant diffusion is assumed to be greater than a tidal period, the scale of the process being studied.

The conversion of dissolved solids can be expressed as

$$D\nabla\cdot(\nabla C) = \frac{\partial C}{\partial t} + \mu\cdot\nabla C$$

where

$$\mu\cdot\nabla C$$

is the advective term and

$$- D\nabla\cdot(\nabla C)$$

is the diffusive term. Assuming the diffusivity of salt and dissolved nutrients in seawater is of the same order of magnitude,

$D \approx 1 \times 10^{-5}$ cm^2/sec (Phillips, 1969), $u \approx 50$ cm/sec, and the length scale L of order 10^4cm, the advective term is approximately 10^{10} greater than the diffusive term. Biological activity, especially with reference to the large spring and somewhat smaller fall bloom, is neglected as to its effects on the concentration of the dissolved nutrients.

The ebb flow has a half tidal cycle average velocity Uo, through an opening half width b (Figure 3). Uo is defined as $\frac{2}{\pi}$ x maximum tidal velocity.

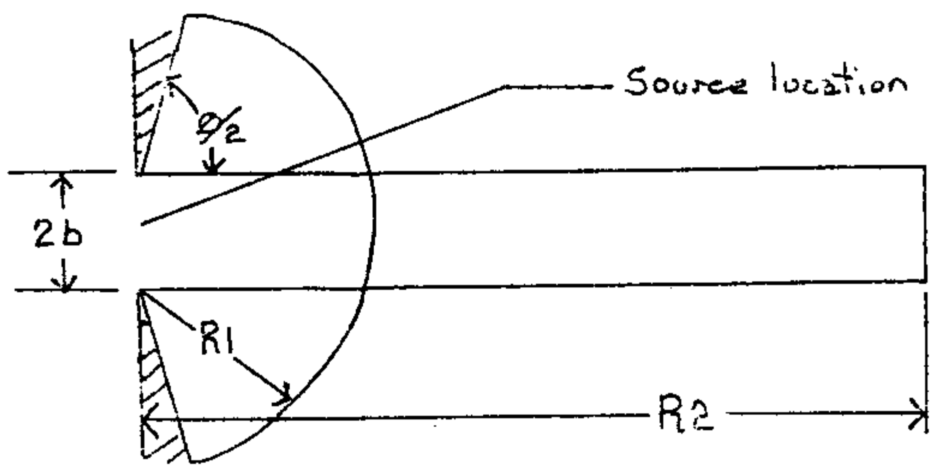

Figure 3

With a half tidal period of time t1, the distance a parcel of water starting at the opening can travel during time t1 is

$$R2 = Uo\ t1$$

The volume of water flowing through the opening is thus

$$V2 = 2bd\ R2 = Uo\ 2bd\ t1$$

where d is the depth of the upper mixed layer.

If Q' is the flux through the opening,

$$V2 = Q' t1 d$$

For the flood tide, let R1 be the maximal radial distance from the opening for a particle to pass through the opening during a flood tide. Let Θ be the angle of the opening for this potential sink. A water parcel in a potential sink has its radial velocity determined by

$$\frac{\partial r}{\partial t} = \frac{-Q'}{\Theta r}$$

where Q', the flux through the opening is defined by

$$Q' = - \int_0^{\Theta} \frac{\partial r}{\partial t} \, r d\Theta'.$$

Integrate from time t = 0, slack water, through flood tide (for flow from the Bay) to time t = t1, high water.

$$\int_{t=0\,(r=R1)}^{t=t1\,(r=0)} r \frac{\partial r}{\partial t} \, dt = - \int_{t=0}^{t=t1} \frac{Q'}{\Theta} \, dt$$

$$\frac{(R1)^2}{2} = \frac{Q't1}{\Theta}$$

or

$$R1 = \left(\frac{2Q't1}{\Theta}\right)^{1/2}$$

but $Q't1 = 2bR2$

$$R1 = 2\left(\frac{bR2}{\Theta}\right)^{1/2}$$

Thus, for a fixed half opening width b,

$$R1 \propto (R2)^{1/2}$$

and note that R2 varies with changing Uo. At the mouth of Boston Harbor by Deer Island, the half tidal cycle average flood velocity varies from 0.36 to 0.75, with a mean of 0.55 meters per second. The ebb velocity varies from 0.20 to 0.66, with a mean of 0.43 meters per second. An ebb velocity of 0.66 meters per second does not necessarily mean the preceding or following flood velocity was 0.75 meters per second. The tides are semi-diurnal with the maximum velocities occuring around the time of the spring tides.

Assume the tides in the harbor have no daily variation in height. Then from conservation of mass equal volumes of water are exchanged between the harbor and the bay on each tidal cycle. Thus V2 is also the volume of the sink flow water, and letting V1 be the volume of the jet water which is not part of the sink flow (Figure 4)

$$V1 = 2bd\ R1 = 4b\ \left(\frac{bR2}{\Theta}\right)^{1/2} d$$

$$V2 = 2bd\ R2$$

The ratio of the volumes

$$\frac{V1}{V2} = 2\left(\frac{b}{\Theta R2}\right)^{1/2}$$

indicates that for a fixed b, an increase in R2 (e.g. Uo) implies a smaller ratio of V1/V2. As will be shown later, the ratio V1/V2 can be thought of as a "sink flushing number". The half width b is assumed to be much less than R2 in order to maintain the assumption of uniform potential sink flow, i.e., a point sink.

2.2 Tidal Exchange Problem

Assume the initial concentration in the harbor of a dissolved nutrient is C(I) at low water. The dissolved nutrient concentration just outside of the harbor mouth of an ebb tide is the sum of the concentration in the harbor and the pollutant flux at the harbor mouth, diluted by the tidal flux and volume flux of the source. Assume the volume flux of the source is much less than the tidal flux, $\frac{E}{Q} << 1$. Then

$$\frac{E}{E+Q} + C(I) \simeq \frac{E}{Q} + C(I)$$

where E is a constant flux of pollutants at the harbor mouth and

$Q = Q'd$

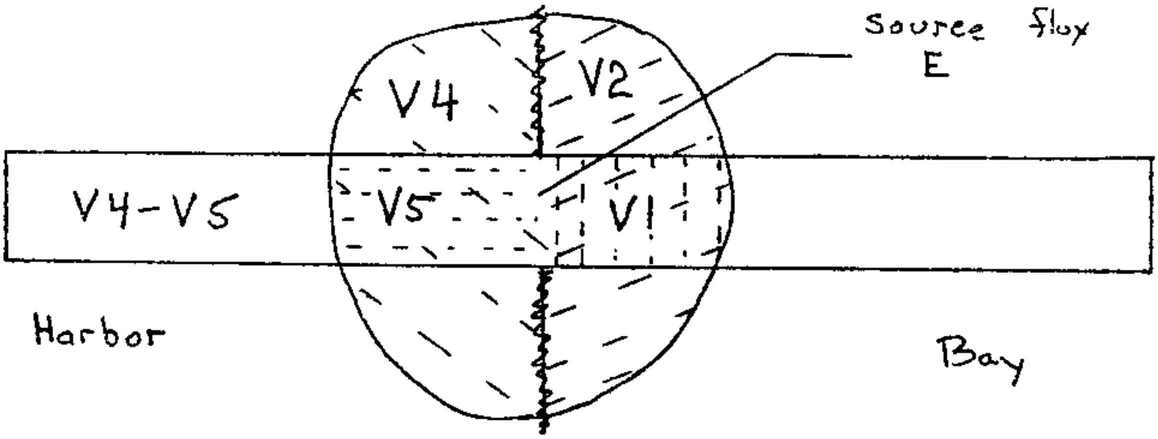

Figure 4

On the flood tide, the water returns to the harbor with a concentration

$$(\frac{E}{Q} + C(I))\ \frac{V1}{V2} + \frac{E}{Q}$$

where the first term is the dilution of the dissolved nutrient concentration with the "clean" water in the bay, and E/Q is the diluted pollution flux as before. From conservation of mass, equal volumes of water are exchanged between the harbor and the bay on each tidal cycle. Assume, also, the nutrients in the harbor volume V5, will not contribute to the low water concentration in the harbor since they will be removed on the next ebb tide. Thus, the concentration in the harbor at low water is

$$C(I+1) = \frac{C(I)\,V3}{V3+V4} + (\frac{E}{Q} + C(I))\frac{V1}{V2}\ \frac{V4-V5}{V3+V4} + \frac{E}{Q}\ \frac{V4-V5}{V3+V4}$$

the water in the harbor is completely and uniformly mixed. On the next flood tide, the inflowing water has concentration

$$(\frac{E}{Q} + C(I+1))\frac{V1}{V2} + \frac{E}{Q}$$

The dissolved nutrient concentration in the harbor is now

$$C(I+2) = \frac{C(I+1)V3}{V3+V4} + (\frac{E}{Q} + C(I+1))\frac{V1}{V2}\frac{V4-V5}{V3+V4} + \frac{E}{Q}\frac{V4-V5}{V3+V4}.$$

The difference in concentrations over a tidal period $\tau(I+1) - \tau(I)$

$$\frac{C(I+1)-C(I)}{\tau(I+1)- (I)} = C(I)(\frac{V4V2-V1(V4-V5)}{(V3+V4)\ V2}) + \frac{E}{Q}\frac{V2(V4-V5)+V1(V4-V5)}{V2(V3+V4)}.$$

Assume a steady state situation, so that $\frac{\Delta C(I)}{\Delta\tau(I)} = 0.$

$$C(I) = \frac{E}{Q}\frac{(V2+V1)(V4-V5)}{V2V4-V1(V4-V5)}.$$

From conservation of mass, and assuming a constant half tidal cycle average velocity, neglecting the volume of the E flux,

$$\frac{E}{Q} << 1, \quad V1 = V5 \quad \text{and} \quad V2 = V4$$

so

$$C(I) + \frac{E}{Q}\frac{(V2)^2 - (V1)^2}{(V2)^2+(V1)^2-V1V2}$$

Expand in a Taylor series,

$$C(I) = \frac{E}{Q}\left[\frac{1}{1-(\frac{V1}{V2} - (\frac{V1}{V2})^2)} - (\frac{V1}{V2})^2\left(\frac{1}{1-(\frac{V1}{V2} - (\frac{V1}{V2})^2)}\right)\right]$$

$$\approx \frac{E}{Q}[1 + \frac{V1}{V2} - (\frac{V1}{V2})^2 - (\frac{V1}{V2})^3 + (\frac{V1}{V2})^4]$$

Assume the dissolved nutrient concentration of the water returning to the harbor on a flood tide has been diluted by the bay water, $V1/V2 < 1$. Then as a rough approximation

$$C(I) \approx \frac{E}{Q}(1 + \frac{V1}{V2})$$

for a steady state situation. Note that for V1 of order V2 the assumptions of point sink flow and dilution of the pollutants are violated.

Going back to the differential equation for C(I), and also again assuming a constant half tidal cycle average velocity, integrate and look for the time development to a steady state.

$$\frac{\Delta C(I)}{\Delta \tau(I)} = - C(I)A_4 + \frac{E}{Q}A$$

where

$$A_4 = \frac{(V2)^2 + (V1)^2 - V1V2}{V2(V2 + V3)}$$

and

$$A + \frac{(V1+V2)(V1-V2)}{V2(V3+V4)}$$

Then

$$\frac{\Delta \tau(I)}{\Delta C(I)} = \frac{1}{-C(I)A4 + E/Q\ A}$$

$$\Delta \tau(I) - \frac{1}{A4}\,\frac{1}{C(I) - (E/Q)(A1A4)} \quad C(I)$$

Integrate, using indefinite integrals

$$\int d\tau(I) = - \int \frac{1}{A4}\,\frac{1}{C(I) + (E/Q)(A/A4)}\,dC(I) + K$$

$$\tau(I) = - \frac{1}{A4}\ln[C(I) + (E/Q)(A/A4)] + K$$

$$C(I) = K'\exp[-A4\tau] + \frac{E}{Q}\,\frac{A}{A4}.$$

Assume that at time $\tau(I) = 0$ (no tidal cycles have elapsed, thwer $\tau(I)$ is the number of tidal cycles), $C(I) = 0$. Then the integration constant K' is

$$K' = - \frac{E}{Q}\,\frac{A}{A4}.$$

Thus

$$C(I) = \frac{E}{Q}\,\frac{(V2)^2-(V1)^2}{(V2)^2+ (V1)^2-V1V2}(1-\exp[-(\frac{(V2)^2+(V1)^2-V1V2}{V2(V2+V3)})\ \tau(I)].$$

Note here that C(I) approaches a steady state concentration asymptotically. Letting $\tau(I) \to \infty$

$$\lim_{\tau(I) \to \infty} C(I) = \frac{E}{Q} \frac{(V2)^2-(V1)^2}{(V2)^2 + (V1)^2 - V1V2} \approx \frac{E}{Q}(1 + \frac{V1}{V2}).$$

Notice this is the same solution derived by assuming a steady state situation from the differential equation.

The e-folding time, $\tau_{e.f.}$, is a measure of how fast a system moves towards an asymptotic value. $\tau_{e.f.}$ is defined as the time required for the dissolved nutrient concentration to reach 1/e times its asymptotic or steady state concentration.

$$C(I) = \frac{1}{e}C_s$$

where C_s is the asymptotic value of C(I).

$$\frac{1}{e} = 1 - \exp(-A4\ \tau_{e.f.})$$

$$\ln(1 - \frac{1}{e}) = -\ Ar\ \tau_{e.f.}$$

$$\tau_{e.f.} = -\frac{1}{A4}\ln(1 - \frac{1}{e})$$

$$\tau_{e.f.} = 0.458\ \frac{1}{A4}$$

$$\tau_{e.f.} = 0.458\ (\frac{V2(V2+V3)}{(V2)^2 + (V1)^2 - V1V2}\ .$$

Again expanding a Taylor series and assuming $V1/V2 < 1$,

$$\tau_{e.f.} = 0.458[\frac{1}{1-(\frac{V1}{V2} + (\frac{V1}{V2})^2)} + \frac{V3}{V2}(\frac{1}{1-(\frac{V1}{V2} + (\frac{V1}{V2})^2)})]$$

$$\tau_{e.f.} \approx 0.458[\frac{V3}{V2}(1+ \frac{V1}{V2}) + (1+ \frac{V1}{V2})]$$

$$\tau_{e.f.} \approx 0.458[(\frac{V3}{V2} + 1)(\frac{V1}{V2} + 1)]$$

The main dependence of the e-folding time is on the volume of the harbor V3, the larger the harbor, the longer the time required to reach a steady state concentration. The sink flushing number, V1/V2, defined as the ratio of the volume of harbor water from an ebb tide which will be returned to the harbor on the following flood tide to the volume of water which flows through the harbor mouth on an ebb tide, has a similar influence on the e-folding time. A smaller sink flushing number leads to a shorter e-folding time.

2.3 Discussion

The main result of this derivation is that the concentration of a pollutant being introduced at the narrow mouth of a harbor, along with the sink flushing number, determines the concentration of that pollutant in the harbor, independent of the volume of the harbor. There is yet to be answered the question of whether the results of this derivation can be used to estimate field observations. There are several factors affecting the flushing number and harbor concentration levels that have not yet been taken into account.

Those dissolved nutrients which are found in the treated sewage effluent being introduced, nitrites, nitrates and phosphates, also exist in Boston Harbor and Massachusetts Bay water at a natural background level. From the inner harbor and the rivers flowing into the harbor, the Charles, Mystic, Neponset and Chelsea, there is also a large source of raw sewage. The natural background count is low during the spring plankton bloom, and not quite as low during the fall bloom. Thus, the problem is to determine what actually is the background level, and if the treated sewage flux of dissolved nutrients is detectable above the background level. The flux of other elements such as trace metals is not routinely measured at the treatment plant, so they can not be used to give another estimate of C(I).

The velocity of the ebb and flood tides in Boston Harbor varies by a factor of about two over a month (Boating Almanac, 1972). The accompanying variations in V1 and V2 will have an effect on the concentrations in the harbor and the e-folding time. With the minimum half tidal cycle average ebb velocity of 0.20 meters per second, and a half width opening b of 730 meters with the angle Θ of $\pi/5$, the sink flushing number V1/V2 is 1.0, while the maximum half tidal cycle average ebb velocityoof 0.66 meters per second, the sink flushing number is 0.55. The mean half tidal cycle average ebb velocity of 0.43 meters per second has a sink flushing number of 0.67. Variations in possible concentrations and e-folding times will be presented with the data and analysis.

A random factor effect is the presence of wind induced surface currents; either moving the pollutants further out to sea, or with an onshore wind, moving them back towards the harbor mouth.

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*This angle was picked from examination of the depth contours on USC & GS survey map #240 of Boston Harbor.

A net alongshore wind would produce Ekman coastal upwelling or sinking.

The baroclinic density circulation is a further factor. Its possible effects will be presented as part of the analysis of cruise 9.

2.4 Dissolved Nutrient - Sigma-t Correlations

One objective of the field observations is to determine the correlation and the physical relation between dissolved nutrient concentrations and the water density, measured as sigma-t.*

The correlation between two random variables x and y is a measure of the linear dependence of x on y. It is given in terms of a correlation coefficient ρ_{xy} defined as the normalized covariance between the variables (Bendand and Piersol, 1971). Letting x denote the nutrient concentration and y the sigma-t value, the correlation between them is the covariance divided by the product of their standard deviations.

$$\rho_{xy} \equiv \frac{Cxy}{\sigma_x \sigma_y}$$

where ρ, C, σ are all continuous functions.

However, since the concentrations and the sigma-t values are obtained from pairs of data points, the sample correlation may be estimated from the sample data by

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*Sigma-t is defined as (density - 1) x 10^3

$$r_{xy} = \text{observed } \rho_{xy} = \hat{\rho}$$

where r_{xy} is the sample correlation coefficient, determined from the data points by

$$r_{xy} = \frac{\sum_{i=1}^{N} (xi-\bar{x})(yi-\bar{y})}{[\sum_{i=1}^{N} (xi-\bar{x})^2 \sum_{i=1}^{N} (yi-\bar{y})^2]^{1/2}}$$

Due to the variability of the correlation estimates, it is desirable to verify a non-zero value of the sample correlcation coefficient r_{xy} in order to determine if the correlation is statistically significant. The test function

$$W = \frac{1}{2} \ln[\frac{1+r_{xy}}{1-r_{xy}}]$$

where W is a random variable with a mean

$$\bar{\mu} = \frac{1}{2} \ln[\frac{1+\rho_{xy}}{1-\rho_{xy}}]$$

and a standard deviation (N = number of data pairs)

$$\sigma w = (N-3)^{-1/2}$$

may be used to evaluate the accuracy of the estimate r_{xy}.

The test hypothesis $\rho_{xy} = 0$ indicates a significant correlation if the hypothesis is rejected. The acceptance region for the hypothesis of zero correlation is

$$- Z_{\alpha/2} \leq \frac{1}{\sigma w} w \leq Z_{\alpha/2}$$

where Z is the standardized normal variable and α is the probability of accepting a false hypothesis.

Values of $\frac{1}{\sigma w} w$ outside the interval would constitute evidence of statistical correlation at the $1 - \alpha$ level of significance.

2.5 Linear Regression

Assuming a linear correlation between dissolved nutrient concentrations and the sigma-t, the next step is to determine the regression equation for nutrient concentration in terms of sigma-t. Using a least-squares fit which minimizes the sum of the squared deviations of the observed values from the predicted values, the predicted value of the concentration $\hat{x}$ is

$$\hat{x} = a + by$$

where y is the measured sigma-t, b is the slope and a is the y intercept. The slope and the intercept are defined by

$$b = \frac{\sum_{i=1}^{N} (yi-\bar{y})xi}{\sum_{i=1}^{N} (yi-\bar{y})^2}$$

and

$$a = \bar{x} - b\bar{y}$$

In order to obtain a theoretical idea of the seaward movement of the water in Boston Harbor, a simple theory for the tidal exchange of waters between the harbor and Massachusetts Bay is developed, using alternating sink and jet flows. Sigma-t -

dissolved nutrient concentrations were derived to look at the feasibility of measuring one variable in order to obtain the distribution of a related variable. It is much easier to obtain the density of seawater by electrical methods, than it is to measure a dissolved nutrient concentration using chemical methods.

The theory forms the basis of the discussion of the data in the next section. However, the data collection was not intense enough to verify the theory, even in its present form.

CHAPTER 3

DATA PRESENTATION AND ANALYSIS

3.1 Deer Island and River Flows

The river flow data was obrained from the United States Geological Survey (USGS) gauging stations located at Waltham for the Charles River, Norwood for the Neponset River and at Winchester for the Mystic and Chelsea Rivers. The correction factors to account for the river inflow in the ungauged areas below the gauging stations (USGS) are 1.2, 1.9 and 2.5 for the Charles, Neponset and Mystic-Chelsea Rivers respectively. The monthly averages are computed from the daily averages for the period from mid December 1972 to mid may 1973; the May average for the Mystic-Chelsea Rivers is estimated from the Charles River average by computing its average fraction of the Charles River flow. The monthly treated sewage effluent flows are from the Metropolitan District Commission Deer Island Treatment Plant monthly records of primary treatment (Table 1a), (Figure 2a).

At high tide there is a large flow of salt water into the sewer system through improperly operating combined storm water and sewage tidal gates which are located mainly in the Boston Inner Harbor (Figure 2) (Hydroscience, 1971). This unregulated flow can be up to 25% of the total treatment plant effluent. It is also heavily chlorinated to kill coliform bacteria.

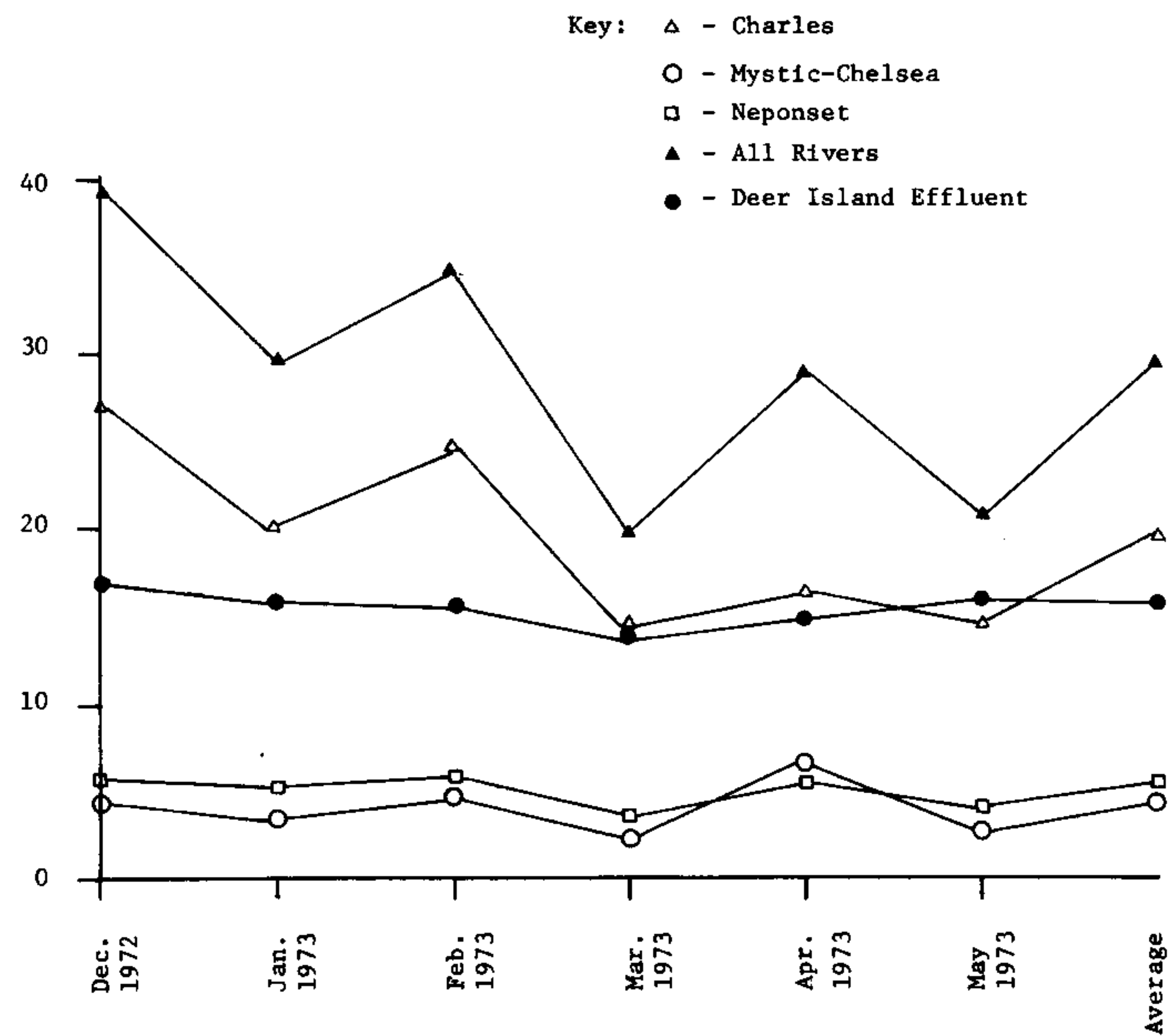


Figure 2a MONTHLY AVERAGE RIVER AND DEER ISLAND FLOWS

This addition of chlorine, without the other ions which constitute seawater, makes the actual determination of salinity nebulous at best, since it is in part based on an empirically derived relation between various ions found in ocean water far from the coasts. The monthly average chlorinity (Table 1b) of 2.95 $^{o}/oo$ corresponds to a salinity of 5.35 $^{o}/oo$ (Knudsen, 1962). This is considered very brackish water.

The major dissolved ions in river water are carbonate, sulfate and calcium, whereas chloride and sodium form only a minor portion of the total dissolved matter (Neumann and Pierson, 1966). Therefore, the addition of large fluxes of unknown ions makes the determination of salinity from chlorinity with great accuracy not possible in the brackish waters found in Boston Harbor and parts of Massachusetts Bay. The use of electronic devices such as a Conductivity-Temperature-Depth sensor still presents the same problems; the relationship between conductivity and temperature and salinity is also empirically derived.

3.2 Estimate of Dissolved Nutrient Concentrations from Theory

From the theoretical presentation, it should be possible to estimate the concentration of a dissolved nutrient in the harbor, given the exchange volumes and fluxes and a source flux. The volume flux of E is taken as the mean monthly average of 15.3 cubic meters per second (Table 1a). Both the exchange flux Q and the sink flushing number are functions of the half tidal cycle average velocity. Table 2 gives various combinations of the source flux E concentrations (Table 1b has spot monthly values of the concentrations) and half tidal cycle average velocities, along with the resulting concentrations that would be present in the harbor. The depth d for the Q flux was assumed to be a constant three meters. Figure 5 is a plot of a non-dimensionalized C(I) versus Uo; the concentration is a function of Uo to the -1 and -3/2 powers, and becomes especially high with a low Uo. Comparing these predicted values of C(I) with the observed concentrations of different dissolved nutrients (Figures 21-24, 26, 33, 39, 48 and 49) it appears the observed values are of the same order of magnitude as what is predicted. However, more dissolved nutrient concentrations in the harbor and a better estimate for the depth of the mixed layer d are needed for a better statistical verification of C(I). The dissolved orthophosphate concentrations appear to be the best tag for the harbor water in the bay, mainly because of their high concentrations in the effluent flux.

The e-folding time for dimensionalized exchange and harbor volume is given in Figure 6. The volume estimate for the harbor is from the Hydroscience report (1971), where the volume is taken for only the northern half of the harbor (Figure 7). The e-folding time varies from three to eleven tidal cycles for Boston Harbor, but that is assuming a constant half tidal cycle average velocity for all the tidal cycles. The actual e-folding time would be that derived from the mean half tidal cycle average velocity, about five tidal cycles.

3.3 Field Observations

3.3.1 Methods of Data Collection

The field investigation in the area of the mouth of Boston Harbor was undertaken with three main objectives: first, to determine the actual distribution of chemical nutrients from the area of the inner harbor out to Massachusetts Bay, second, to attempt to verify the flushing theory just presented and third, to determine if it is feasible to estimate the nutrient distribution (a time consuming chemical analysis) by correlation of the dissolved nutrient concentration with another variable that can be measured easier electrically, e.g., sigma-t.

Cruise 1 (August 16-17, 1972) was made for a background study. Work was attempted during the winter, but rough seas made small vessel data collection difficult. On Cruise 6 (March 15, 1973) the area coverage outside Boston Harbor was more extensive, but no CTD casts were made, only surface temperature, salinity and nutrient samples were taken. Cruises 7, 8 and 9 covered essentially the same area, but included both CDT casts and nutrient samples; on Cruise 7 nutrient samples were taken at the surface, on Cruise 8 they were taken at one and one-half meters and on Cruise 9 they were taken at both the surface and three and one-half meters.

All field work was carried out on the Massachusetts Institute of Technology RV R. R. Shrock, using CTDs built by the M.I.T. meteorology department. The temperature and pressure calibrations were done mechanically, the conductivity calibrations were done electrically. No attempt was made to take salinity bottle samples due to the brackish nature of the harbor and effluent water. Thus, the salinity and sigma-t values obtained are only relative to each other and should not be considered as absolute values. The data was recorded in analog format on the ship, along with a reference clock signal. On shore it was transformed into a digital format on a Honeywell mini-computer. Final processing was accomplished on a PDP-7 computer to obtain station listings and temperature and salinity versus depth, sigma-t versus depth and temperature versus salinity plots. The conversion of temperature, conductivity and pressure into salinity and sigma-t was done using a standard Woods Hole Oceanographic Institute computer subroutines (in use in 1972). Since the work was undertaken in shallow water the assumption was made that 1.0 decibar of pressure was equivalent to 1.0 meters of depth. For a pressure of 30 decibars, 30.0 db. = 29.77 m., the error would be only 0.9% (Neumann and Pierson, 1966). The dissolved chemical nutrient concentrations were determined using a Technicon Autoanalyzer. The salinity of the surface samples from Cruise 6 were determined with a Bissett-Berman benchtop salinometer.

3.3.2 Cruise 1

Cruise 1 was on August 16-17, 1972, and consisted of four runs from the inner harbor to outside the mouth of the harbor (Figure 8). The stations 5, 15, 25, 35 are located at the Deer Island Treatment Plant outfall.

On run 1 (Figures 9-11) the inversions and other small anomalies present are due to the brackish water; they are shown on the sections to exhibit the data collected, some of the smaller ones have been removed. The anomalies are probably due to the methods of measurement. Seaward, at Station 9, the pool of warm, fresh and light water on the surface is probably effluent from the previous ebb tide coming back on the present flood tide. The warm and fresh river water coming through the inner harbor has mixed with the water in President Roads and lost its distinguishing characteristics by Station 4. From Station 4 the Deer Island effluent presents itself as a new source of fresh, warm water.

Run 2 (Figures 12-14) was made at high water. The main feature is the pool of warm, fresh water forming above the Deer Island outfall (Station 15).

The third run (Figures 15-17) was taken half way into the ebb tide. At Stations 25-27, the pool of fresh, warm water on the surface is part of the Deer Island effluent. Warm, fresh river water has moved from the inner harbor into President Roads, (Stations 21-24) but the Deer Island effluent still presents itself as a new water source at Station 25.

The final run (Figures 18-20) was at the end of the ebb tide, essentially low water. The light effluent water is present at Station 35, Deer Island, and also furter seaward as a pool centered at Station 37. The density inversion at Stations 38-39 is probably from the brackish nature of the water. The very warm pool (16°C) is power plant cooling water, coming from the southwest of Station 33. The Deer Island effluent is still separable as a new source of warm water.

To summarize the hydrographic stations from Cruise 1, Deer Island water is a source of warm, light and brackish water which rises to the surface, moves seaward with the ebb tide, where it mixes somewhat with the bay water, and then comes back towards the harbor on the subsequent flood tide. The river inflow and the power plant cooling water are mixed with the surrounding waters before Deer Island, thus the Deer Island

Treatment Plant water is easily traced as a new source of high temperature and low salinity; low density water.

On the surface samples for this cruise, the nitrite concentrations were determined (Figures 21-24). Referring to what has been described in the vertical sections, the horizontal sections of the nitrite concentrations show the movement of the effluent as a separate water mass. On run one, during the beginning of the flood tide, an area of high concentration outside the harbor is separated from the harbor by an area of low concentration. Going to slack water, run two, the concentration outside the harbor has decreased, while the levels inside the harbor itself have remained essentially the same. On the ebb tidal flow during run three, the concentrations outside the harbor are building up, while the concentrations in the harbor, especially near the inner harbor, are also increasing. The increase of the concentrations near the inner harbor is from the high levels of pollution in the inner harbor (Hydroscience, 1971, Environmental Protection Agency, 1971). At low water, run four, the concentrations both in the harbor and outside of it are uniformly ligh.

3.3.3 Use of only Sigma-t

Sigma-t will be used in the presentation of the remaining sections mainly for simplicity. As has been shown in the analysis of Cruise 1, the Deer Island effluent water is of very low salinity and is warmer than the surrounding waters, corresponding to a very low sigma-t value. This low sigma-t water is separable from the river inflow water. Thus, the Deer Island water can be traced by either temperature and salinity or by sigma-t alone.

3.3.4 Cruise 6

Cruise 6 (Figures 25-26) on March 15, 1973 was during the period from ebb tide to slack water. No CTD stations were made due to minor equipment problems, but surface samples were taken for nitrite concentrations, salinity and temperature. The salinity and temperature were converted into sigma-t using Knutsen's Hydrographical Tables (1962). The effluent has gone to the northeast during this cruise, as can be noted from the curvature of the 24.0 isopycnal to the east and the high nitrite concentrations in the same area.

3.3.5 Cruise 7

Cruise 7 on April 19, 1973 was centered around slack water at high tide. The data is presented as longitudinal section B, transverse sections E, F and G, and surface nitrite plus nitrate concentrations (Figures 27-33).

In section B a strong outflow of the Deer Island effluent shows at Station3. The seasonal pycnocline is just beginning to develop, and it is at two and one-half to three meters depth, except at Station 7 where it rises to within a meter of the surface. Section E has a core of light (26.4 sigma-t) Deer Island water which essentially disappears at Station F, but reappears further seaward on Section G. The 26.4 sigma-t water in section G is probably from the previous ebb tide, and is separated from the landward 26.4 sigma-t water of the present ebb tide by denser water from the bay which mixed in during the flood tide.

The horizontal sections of the 1.0 meter sigma-t and surface nitrites plus nitrates also shows this apparent separation of the ebb tidal flows. The seaward rise, fall and rise of the nutrient concentrations corresponds very well to the inverse fall, rise and fall of the sigma-t values.

3.3.6 Cruise 8

On Cruise 8, from high water to maximum ebb flow on May 3, 1973, the vertical sections F, G and H and the one and one-half meter orthophosphates represent the data collected (Figures 34-39). The lack of data closer to the harbor makes it difficult to conclude much about the movement of the Deer Island effluent water. On section G a pool of 24.6 sigma-t water appears to be Deer Island effluent. The horizontal orthophosphate section shows this water may be from the previous ebb tide, and is presently being dispersed. The center of the high orthophosphate concentration water is landward of section G.

On Section H, the furthest west of any section taken on any of the cruises, the pycnocline (at approximately 25.2 isopycnal) is at five meters depth. Assuming it has been present for an inertial period (14 hours, approximately at 42°N), below fifteen meters a weak geostrophic current is flowing eastward.

3.3.7 Cruise 9

The last cruise, 9, on May 23, 1973 was centered around high water. The data consists of longitudinal section B, transverse sections C, E, F and G, and surface and three and one-half meter orthophosphate horizontal sections (Figures 40-49).

Section B shows the release of Deer Island effluent between Stations 3 and 4. The pool of less than 24.6 sigma-t water below ten meters on these two stations is probably due to the chemical composition of the water, and may not be real. The pycnocline rises from fifteen meters at the seaward end of the section, Station 21, and then drops to meet the bay floor just outside the harbor at Station 5. The 24.6 sigma-t water on sections C and E disappears by section F. The apparent inversion in section E, centered at Station 10, is again due to the composition of the brackish Deer Island effluent water.

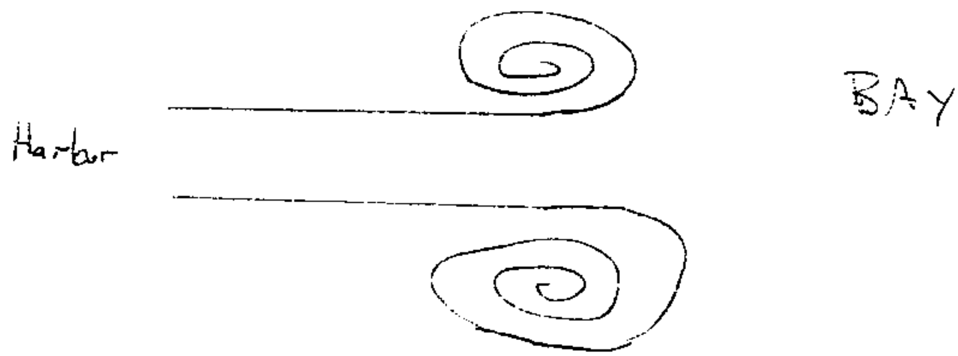
On the seaward sections E, F and G the pycnocline (25.4 isopycnal) tilts upward to the southeast. Assuming this feature has existed for an inertial period, the geostrophic current was calculated between Stations 21 and 22 on section G (Figure 45) (Tables 3a, 3b, 3c). (See Neumann and Pierson, 1966, for a detailed explanation of the calculation).

Fourteen meters was used as the reference level of no motion. Down to that level there is a current with a 2.6 centimeters per second maximum velocity away from the harbor.

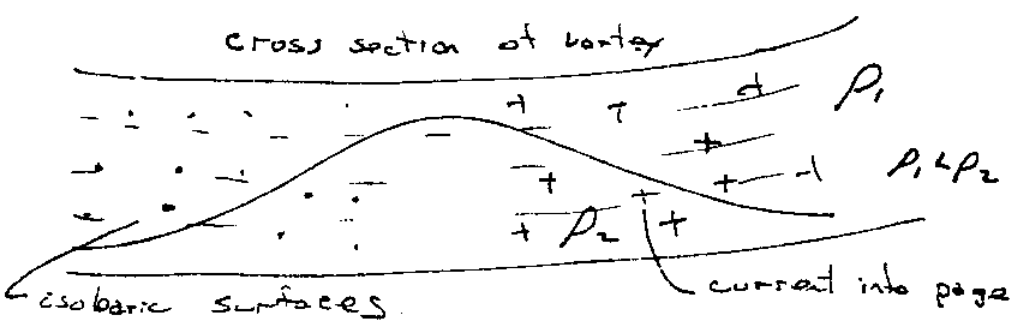
Below fourteen meters a current of up to 7.7 centimeters per second is moving in the opposite direction towards the harbor. Since and anomaly of the specific volume δ was averaged over one meter intervals, a slight possible error in the zeroing of the depth measurements of up to a possible one-fourth meter would not have any significant effect on the net result of the computations. A relative easterly geostrophic flow exists down to fourteen meters, and a stronger westerly flow is present below that level.

The orthophosphate sections indicate a pool of high concentration outside the harbor, along with very high concentrations in the harbor at President Roads. The pool of high concentration outside the harbor may be from the previous ebb flow, while the high concentrations in President Roads is due to the release of Deer Island effluent during the present flood tide.

The three and one-half meter orthophosphate and the 1.0 meter sigma-t sections show a tongue of high phosphate, low sigma-t water moving out of the harbor, and also a pool of low phosphate-high sigma-t water centered about Station 9, section E. The 10.0 meter sigma-t section shows a rise of the isopycnal surfaces about the same area, implying the possibility of very light surface water; the isopycnal surfaces rising to maintain the hydrostatic balance. Another possibility is the rising of the 10.0 meter isopycnal surfaces may be due to vortex type motion, perhaps from the start up of the ebb tidal jet.



The faster moving light upper water creates a low pressure like area, allowing the dense lower water isopycnal surfaces to rise.



Section C has the interesting feature of "V" shaped isopycnals. Assuming an inertial period to set up, a current is flowing into the harbor along the southeastern edge of the harbor mouth, and a current is flowing out of the harbor along the northwestern edge. The inertial period required to set up a geostrophic current is about fourteen hours and the tidal velocities through section C are up to one meter per second; the shape of the isopycnals may be due to tidal action alone. A geostrophic current of about ten centimeters per second would have only a small effect on the analysis of the tidal exchange problem.

The disappearance of the high orthophosphate water by section F corresponds to the loss of the 24.6 sigma-t water.

3.3.8 Aerial Observations

On Cruise 9 during the return into Boston Harbor (one and one-half hours into ebb tide) there was a visual sighting of a surface slick which appeared to originate above the location of the outfall (Figure 50). A photograph taken at that time (Figure 51) shows the slick in the foreground, and the rougher water in the background, beginning at the Deer Island light. The rougher water (capillary waves present) had also just been passed through by the ship.

Subsequently, on May 26, 1973, photographs were taken of the Deer Island effluent plume from a commercial flight from Logan International Airport, Boston. One-half hour into ebb tide, the plume extends from inside the harbor entrance, on the right, to outside the harbor (Figure 52). The next photograph (Figure 53) was taken a minute or so later, the wake of the freighter has stirred water up from below the plume, showing it to be only a surface feature.

3.3.9 Wind Induced Surface Currents

Neumann and Pierson (1966) give an empirical formula for the surface drift currents induced by wind stress, derived by Thorade. The dependence of Vo, the induced current, on latitude ϕ is

$$Vo = \frac{2.59\ \sqrt{w}}{\sqrt{\sin\ \phi}} \qquad w \leq 6\text{m/sec (approx.)}$$

$$Vo = \frac{1.26w}{\sqrt{\sin\ \phi}} \qquad w > 6\text{m/sec}$$

where Vo is given in centimeters per second if w, the wind speed, is measured in meters per second. The mean wind and surface currents (Table 4) are from Logan Airport, located north of President Roads. The twelve and twenty-four hour averages are for these periods preceeding the last station of the cruises. The velocities from the RV R. R. Shrock are averaged from the half hourly readings taken during the cruises.

The surface currents, using the Logan data, averaged from 5.2 to 6.6 centimeters per second; a water parcel would travel 1200 to 1500 meters during a 6.3 hour tidal period. With a tidal excursion (R2) of ten thousand meters and an easterly or westerly wind, the variation in R2 would be approximately ten percent. The effect is relatively small, but a knowledge of the recent and predicted winds would lead to a better ability to predict the nutrient concentrations in the harbor. The derivation of the original theory was fairly crude, thus no attempt was made to predict the minor effects of the wind induced surface currents.

3.4 Dissolved Nutrient - Sigma-t Correlations

The dissolved nutrient concentrations and the one meter sigma-t values were correlated for cruises 1, 6, 7, 8 and 9. The correlations, number of data points measured and α, the probability of accepting a false hypothesis, are listed in Table 5.

The low level of significance for Cruise 8 is from the low number of data pairs (nine) and thus will not be discussed further. Cruises 1, 7, and 9 present high correlations with 95% levels of significance (5% α). Cruise 6, with a somewhat lower correlation, still has a 70% level of significance.

From this correlation data, and both the horizontal and vertical sections showing evidence of pools of high nutrient concentrations corresponding to pools of low sigma-t, there is a strong correspondence between dissolved nutrient concentrations and sigma-t values.

However, caution must be exercised before going out in the field and measuring the sigma-t values to conclude what the nutrient concentrations are. Sigma-t values change significantly during the year due to the spring runoff into the bay, and the late fall overturning. A mapping of the surface sigma-t values would make it possible only to conclude the relative values of the nutrient concentrations. From these, it would be possible to identify and follow the Deer Island effluent water mass.

3.5 Sample Regression

As a test of the visual quality of the regression analysis, a least squares linear regression of concentration of dissolved orthophosphates on sigma-t was performed on the 1.0 meter sigma-t data from Cruise 9 (Figure 54). The equation for concentration C from sigma-t is

$$C = 39.9259 - 1.5315\ (\text{sigma-t}).$$

The regression orthophosphates do not define the Deer Island effluent as well as the observed concentrations, but the effluent is still evident.

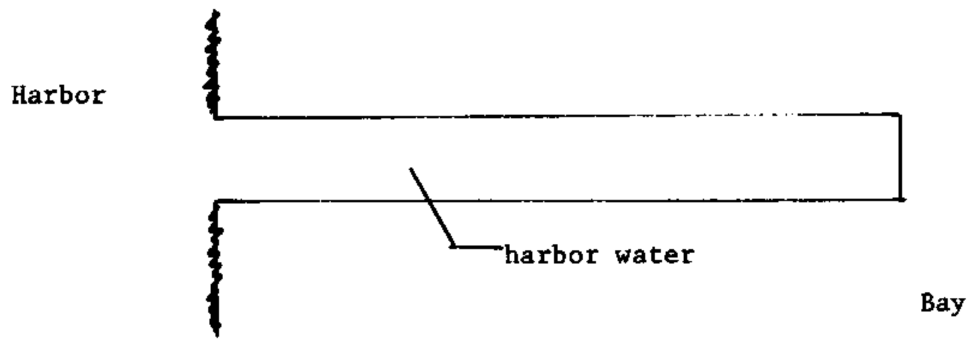
CHAPTER 4

RESULTS

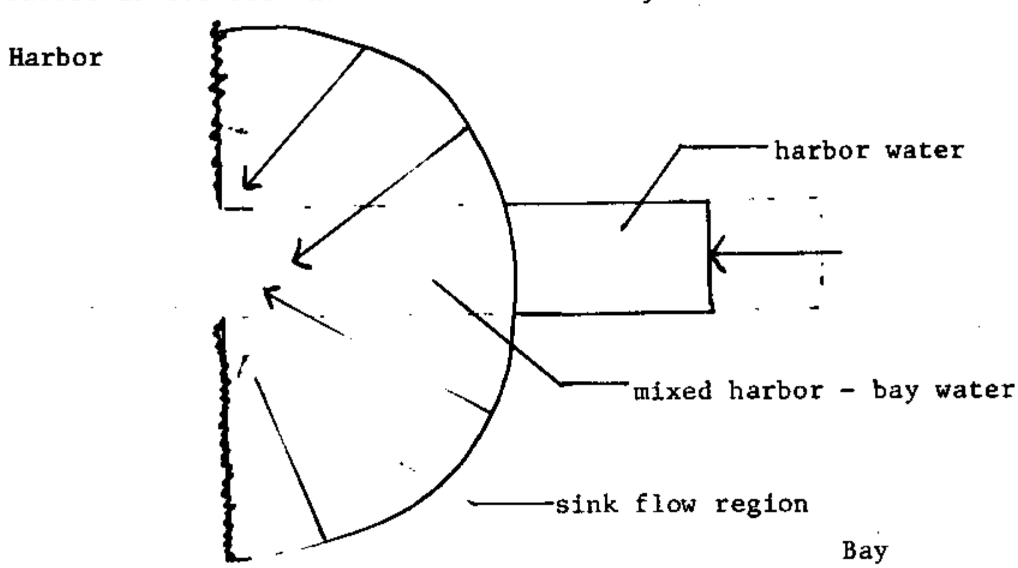
4.1 Release of "Blobs"

If the surface chemical data from Cruise 1 is referred to (figs. 21-24), there is the movement of what appear to be "blobs" of harbor water seaward. Following is a schematic times series of what may be occurring.

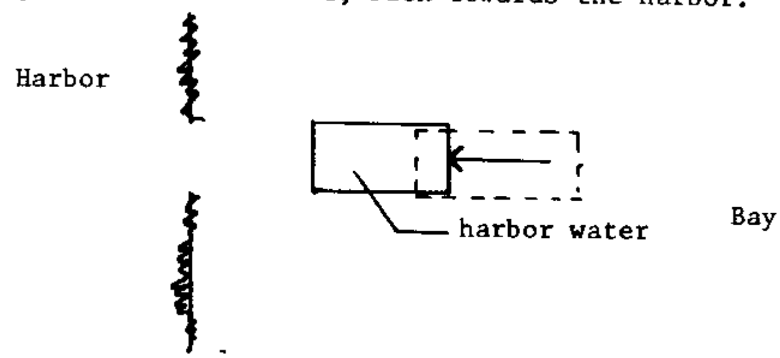
At ebb tide, low water, a long tongue of harbor water protrudes into the bay.



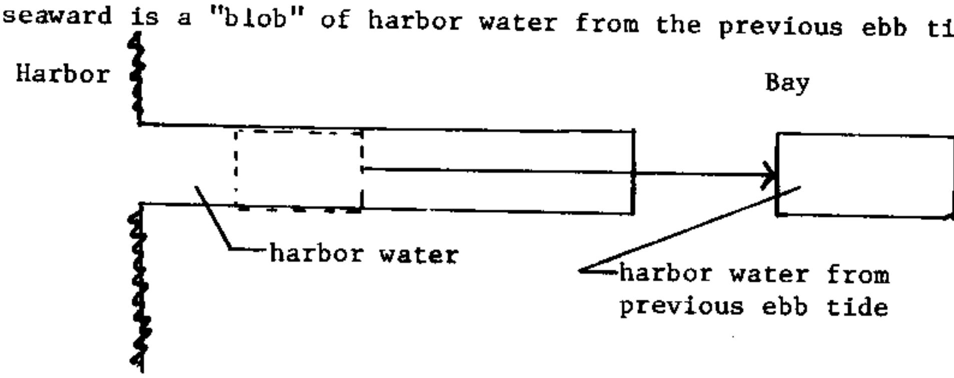
During the flood tide, the sink flow mixes harbor and bay water near the harbor, while the harbor water further seaward is cut off and remains essentially unmixed.



At slack water, high tide, the harbor water mass in the bay has moved landward, back towards the harbor.



At the second ebb tide low water, a long tongue of harbor water is again protruding into the bay, and further seaward is a "blob" of harbor water from the previous ebb tide.



A rough estimate of the size of the homogenous harbor water mass, the "blob", is 2000 to 4000 meters long and 1500 meters wide. It is at present impossible to estimate the spacing of the "blobs" further out in the bay due to lack of sufficient data.

Edmonds (1973) has reported anomalies of dissolved nutrient concentrations in north-south sections in the region of sections G and H, Cruise 8 (fig. 34). These anomalies may be from "blobs" of harbor water moving seaward.

CHAPTER 5

SUMMARY AND CONCLUSIONS

A simple theoretical model for concentration in a harbor of a source flux at the harbor mouth was derived. Field observations consisting of five cruises were made in Boston Harbor and adjacent Massachusetts Bay. One hundred stations were taken, most with both a CTD and nutrient bottle samples. Since the water being investigated was very brackish, no salinity bottle samples were taken to check the conductivity (salinity) calibrations of the CTD.

Wind induced surface and possible bottom geostrophic currents were calculated; they were found to be less than ten centimeters per second. The hydrographic data was summarized in vertical sections, the nutrient data in horizontal sections. A computation of C(I), the theoretical concentration of dissolved nutrients in the harbor, was compared to the observed values.

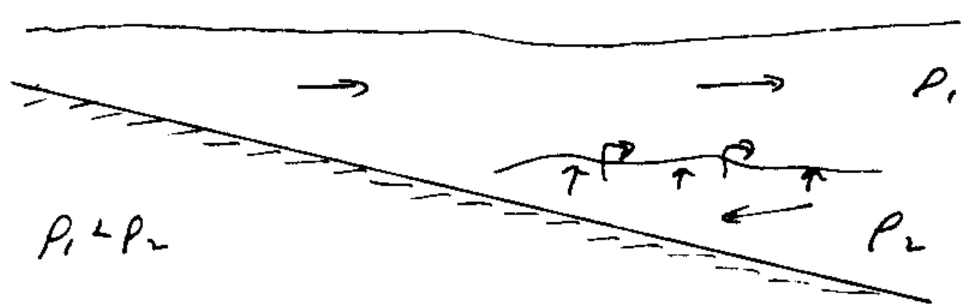
The conclusions, in no particular order, are:

1) From the theoretical derivation, the concentration of a flux source at the mouth of a basin-shaped harbor with strong tidal currents, and the sink flushing number determine the concentration of that source in the harbor itself, independent of the volume of the harbor.

2) In Boston Harbor, with river and source fluxes of the same magnitude and separated spatially, the effluent source is a separate water mass and may be so identified by hydrographic observation.

3) The Deer Island effluent source, and possibly the harbor water move seaward as large homogenous water masses, "blobs", one "blob" being emitted on each ebb tide.

4) An apparent geostrophic current of up to ten centimeters per second exists below the pycnocline in Massachusetts Bay, flowing towards the harbor at the time of observation. From the conservation of salt mass, this water may mix with the above lying water by entrainment and vertical advection, subsequently flowing out to sea.



5) From aerial observations, the effluent does not mix immediately with the harbor water flowing through the harbor mouth at Deer Island. The effluent is a distinct water mass which floats on the harbor and bay water, slowly mixing with them by diffusion. The theoretical derivation had assumed uniform and complete mixing of the harbor water and Deer Island effluent, especially in the harbor itself.

This report represents just a beginning of a study of the circulation between Boston Harbor and Massachusetts Bay, and a greater study of the circulation in the bay as a whole.

Areas for further investigation started by this study are:

1) The movement of the harbor water and effluent as "blobs" seaward, and the diffusion of the "blobs" into the surrounding waters, possibly by aerial observation.

2) The effects of the geostrophic currents on the general circulation, possibly by a synoptic survey over several tidal periods. Along with this, a month long survey to determine the effects of the monthly tidal velocity variations.

3) Use of a hydroglider (Mollo-Christense, 1972) for rapid hydrographic coverage of a much expanded area of study.

4) A better calibration of the CTD, possibly with salinity bottle samples on each cast and a correction for brackish water.

5) The effects of storm surges on the nutrient concentrations in the harbor.

6) The possibility of vortices in the bay, formed by the start up of the ebb tidal jet.

7) A sink flow model which does not break down for $2b \approx R2$, the jet excursion distance.

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Table 1A

Monthly Average River and Deer Island Effluent Flows

River	Charles	Mystic-Chelsea	Neponset	All Rivers	Deer Island Effluent
December 1972	27.9	4.8	6.7	39.4	17.2
January 1973	20.6	3.5	5.1	29.2	15.9
February 1973	23.8	4.8	5.7	34.3	15.2
March 1973	14.1	2.3	3.1	19.5	13.6
April 1973	16.8	6.7	5.1	28.6	14.6
May 1973	14.7	2.5	3.7	20.9	15.4
Average	19.7	4.1	4.9	28.9	15.3

All values in cubic meters per second

Table 1B

Spot once-a-month Effluent Chemical Concentrations

Month	Chloride (‰)	Month	Nitrate ppm	Orthophosphate ppm	Nitrite ppm
August 1972	3.0	June 1972	0.27	4.2	0.061
September 1972	3.2	July 1972	0.23	3.8	0.053
October 1972	3.3	December 1972	0.30	4.7	0.062
November 1972	2.8	January 1973	0.84	4.9	0.086
December 1972	2.3	February 1973	0.35	3.1	0.055
January 1973	2.6	March 1973	0.90	2.7	0.080
February 1973	2.8	April 1973	0.60	2.2	0.050
March 1973	3.3	May 1973	0.60	2.0	0.040
April 1973	3.1	June 1973	0.70	0.1 (*)	0.040
May 1973	3.1				
Average %	2.95	Average (ppm)	0.53	3.5	0.059
Average μ gm. atm./l.			29.5	192	3.3

The chloride concentrations are true monthly averages. The other chemical concentrations are from samples that are taken once-a-month.
* This value was not used in determination of the average orthophosphate concentrations because of its large deviation from the mean value.

Table 2

Predicted values of dissolved nutrient concentrations in Boston Harbor from theory. The tidal velocities are the maximum, mean, and minimum hftc. The values of E are from the average of the spot monthly values.

E μ gm. atm./l.	Uo meters per second	C(I) μgm. atm./l.
192 Orthophosphates	0.66 0.43 0.20	1.58 2.60 6.68
29.5 Nitrates	0.66 0.43 0.20	0.243 0.400 1.026
3.3 Nitrites	0.66 0.43 0.20	0.0269 0.0448 0.1146

Table 3A

Station 21 Cruise 9

DEPTH	SIGMA-t	$\delta \times 10^5$	$\bar{\delta} \times 10^5$ $\bar{\delta} \equiv \Delta D$ *	$\Sigma \Delta D \times 10^5$
1	24.684	327.0		0.0
			324.8	
2	24.656	329.8		328.4
			329.5	
3	24.661	329.3		657.9
			323.1	
4	24.790	316.9		981.0
			311.3	
5	24.908	305.3		1292.1
			302.2	
6	24.978	299.1		1594.3
			294.3	
7	25.078	289.5		1888.6
			287.3	
8	25.102	287.2		2175.9
			283.1	
9	25.187	279.1		2459.0
			280.6	
10	25.156	282.1		2739.6
			282.1	
11	25.156	282.1		3021.7
			280.6	
12	25.187	279.1		3302.3
			275.0	
13	25,273	271.0		3577.3
			262.0	
14	25.462	253.0		3839.3
			244.2	
15	25.647	235.4		4083.5
			222.9	
16	25.909	210.5		4306.4
			202.9	
17	26.070	195.3		4509.3

* $\bar{\delta}$ is eqivalent to ΔD since the depth interval is one meter

Table 3B

Station 22   Cruise 9

DEPTH	SIGMA-t	$\delta \times 10^5$	$\overline{\delta} \equiv \Delta D \times 10^5$ *	$\Sigma \Delta D \times 10^5$
1	24.730	322.7		0.0
			324.4	
2	24.714	324.1		323.4
			321.1	
3	24.778	318.1		644.5
			315.1	
4	24.840	312.2		959.6
			304.9	
5	24.993	297.6		1264.5
			293.3	
6	25.082	289.1		15578
			288.7	
7	25.090	288.4		1846.5
			288.3	
8	25.091	288.3		2134.8
			287.5	
9	25.107	286.7		2422.3
			285.0	
10	25.143	283.3		2702.3
			283.8	
11	25.132	284.3		2991.1
			283.8	
12	25.143	283.3		3274.9
			281.8	
13	25.174	280.4		3556.7
			278.0	
14	25.225	275.6		3834.7
			269.9	
15	25.343	264.3		4104.6
			261.8	
16	25.393	259.3		4366.4
			253.8	
17	25.510	248.4		4620.2

* $\overline{\delta}$ is equivalent to ΔD since the depth interval is one meter

Table 3C

Geostrophic current from field of mass between stations 21 and 22, Cruise 9.

Depth	$(\Sigma\Delta D_{21} - \Sigma\Delta D_{22}) \times 10^5$	Relative Current cm./sec.	Current with respect to 14 m. level cm./sec.
1	0.0	0.0	-0.3
2	5.0	0.3	0.0
3	13.4	0.8	0.5
4	21.4	1.3	1.0
5	27.6	1.7	1.4
6	36.5	2.3	2.0
7	42.1	2.6	2.3
8	41.1	2.5	2.2
9	26.7	1.6	1.3
10	32.3	2.0	1.7
11	30.6	1.9	1.6
12	27.4	1.7	1.4
13	20.6	1.3	1.0
14	4.6	0.3	0.0
15	-21.1	-1.3	-1.7
16	-60.0	-3.7	-4.0
17	-120.9	-7.4	-7.7

Distance between the stations is 1655 meters, $\phi = 42^{\circ}\ 20'$ North.

Table 4

Wind Induced Surface Currents

Cruise 6		Cruise 7		Cruise 8		Cruise 9	
15 March 1973		19 April 1973		3 May 1973		23 May 1973	
Wind	Current	Wind	Current	Wind	Current	Wind	Current
12 hour 3.2 m/sec 110°	5.7 cm/sec	12 hour 2.7 m/sec 220°	5.2 cm/sec	12 hour 2.6 m/sec 160°	5.1 cm/sec	12 hour 4.2 m/sec 230°	6.5 cm/sec
24 hour 2.7 m/sec 110°	5.2 cm/sec	24 hour 3.0 m/sec 220°	5.5 cm/sec	24 hour 2.8 m/sec 150°	5.3 cm/sec	24 hour 4.3 m/sec 260°	6.6 cm/sec
		RR Shrock 5.4 m/sec	7.3 cm/sec	RR Shrock 2.7 m/sec	5.2 cm/sec	RR Shrock 7.6 m/sec	11.6 cm/sec

$\phi = 42^\circ\ 20'$ The twelve and twenty-four mean winds are from Logan International Airport, Boston for that period of time preceeding the last station of the cruises. The mean winds from the RR Shrock are from half hourly readings during the cruises.

Table 5

Correlations between dissolved nutrient concentrations and sigma-t, and the probability of accepting a false correlation.

Cruise	Variables	# of data pairs	Correlation	Prob. of accpt. false correlation (α)
1	surface nitrite 1.0 meter sigma-t	26	-0.7825	0.0
6	surface nitrite surface sigma-t	14	-0.4515	0.3046
7	surface nitrite plus nitrate 1.0 meter sigma-t	14	-0.6559	0.0580
8	1.5 m. ortho-phosphate 1.0 m. sigma-t	9	0.5478	0.8220
9	surface ortho-phosphate 1.0 m. sigma-t	23	-0.7941	0.0
9	3 1/2 m. ortho-phosphate 1.0 m. sigma-t	22	-0.8567	0.0
9	3 1/2 m. ortho-phosphate surface ortho-phosphates	22	0.8946	0.0

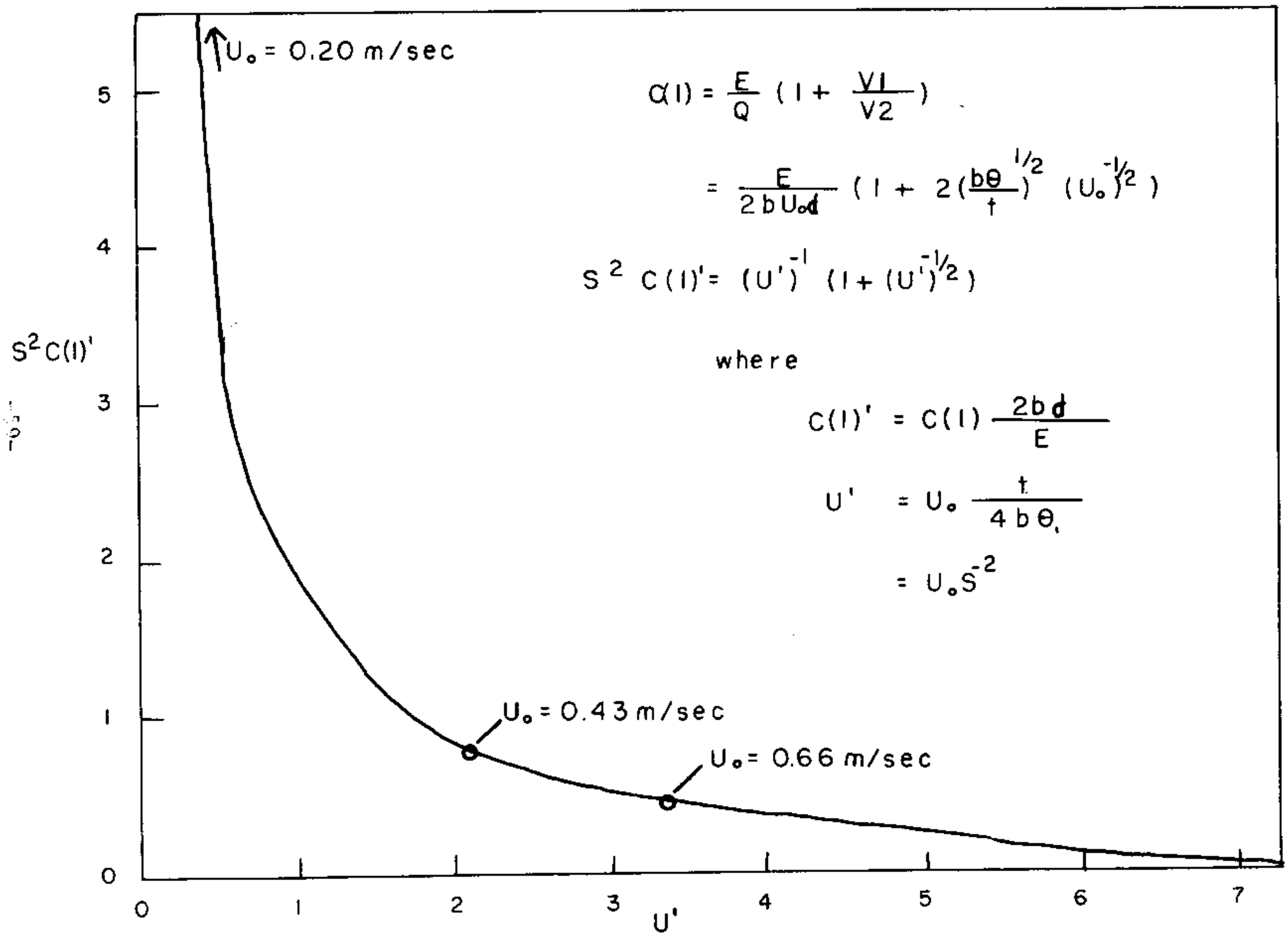


Figure 5 non-dimensionalized Uo versus C(I)

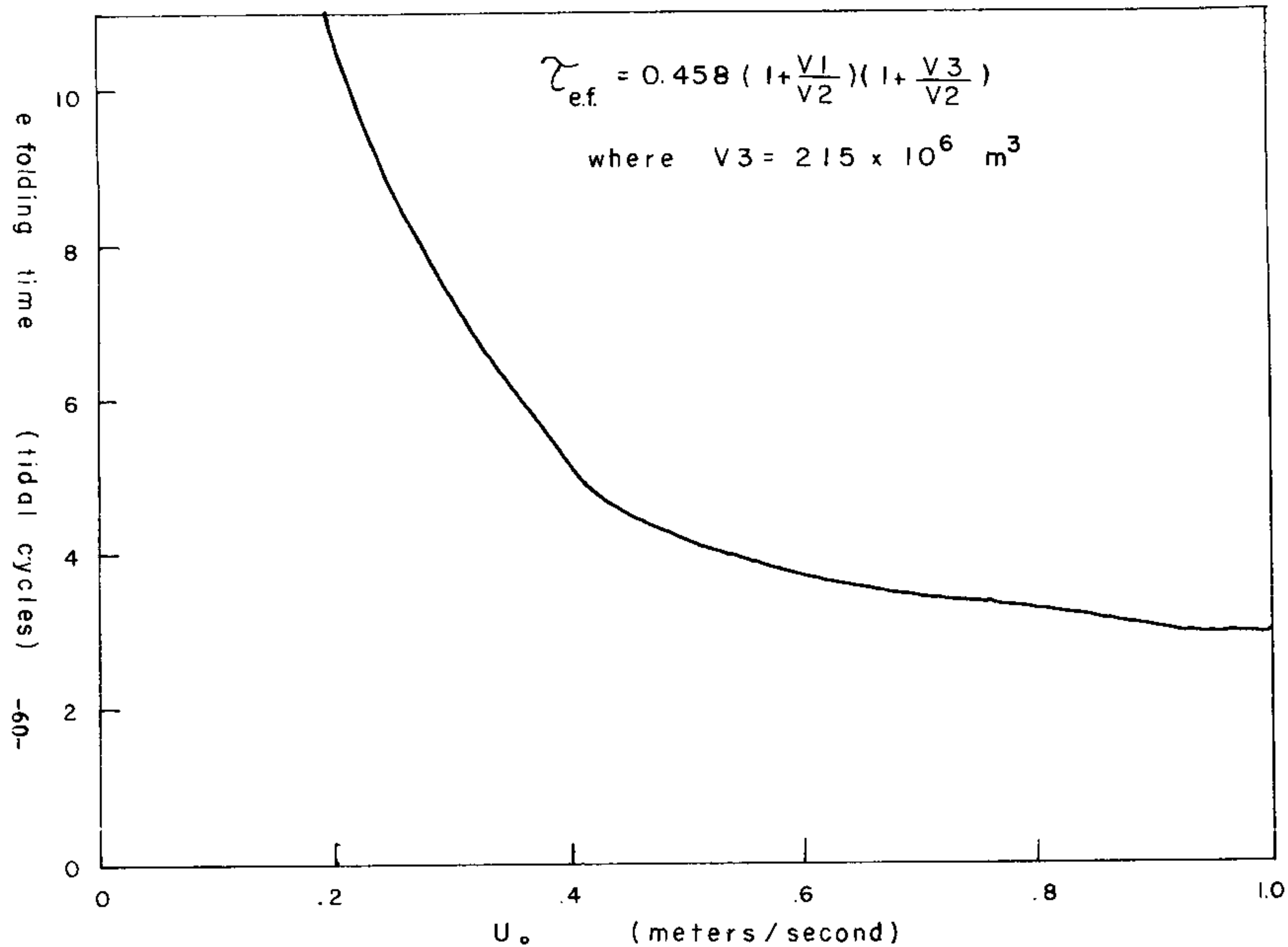


Figure 6 e-folding time versus rms tidal velocity

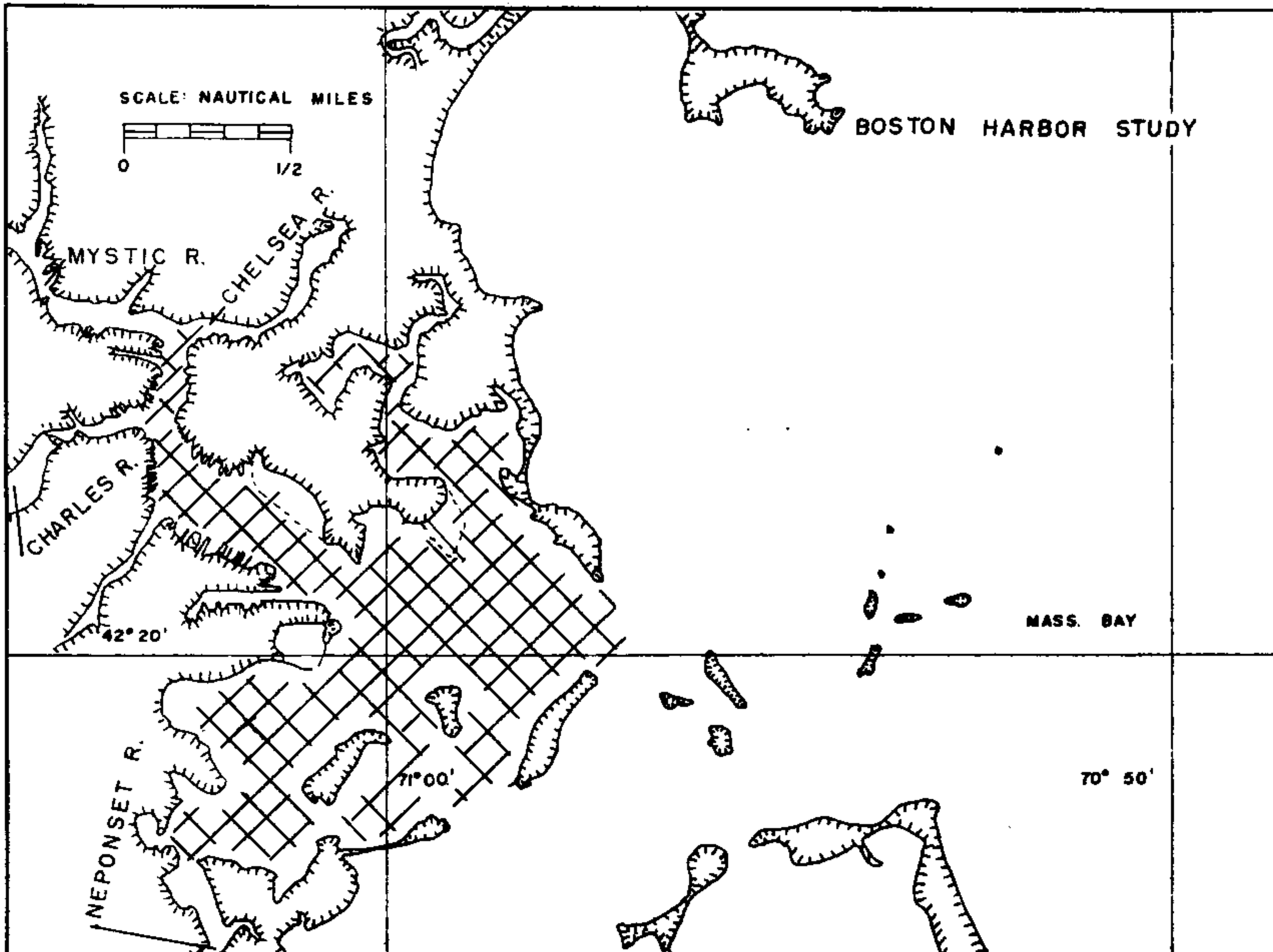


Figure 7 VOLUME (V3) FOR E-FOLDING TIME

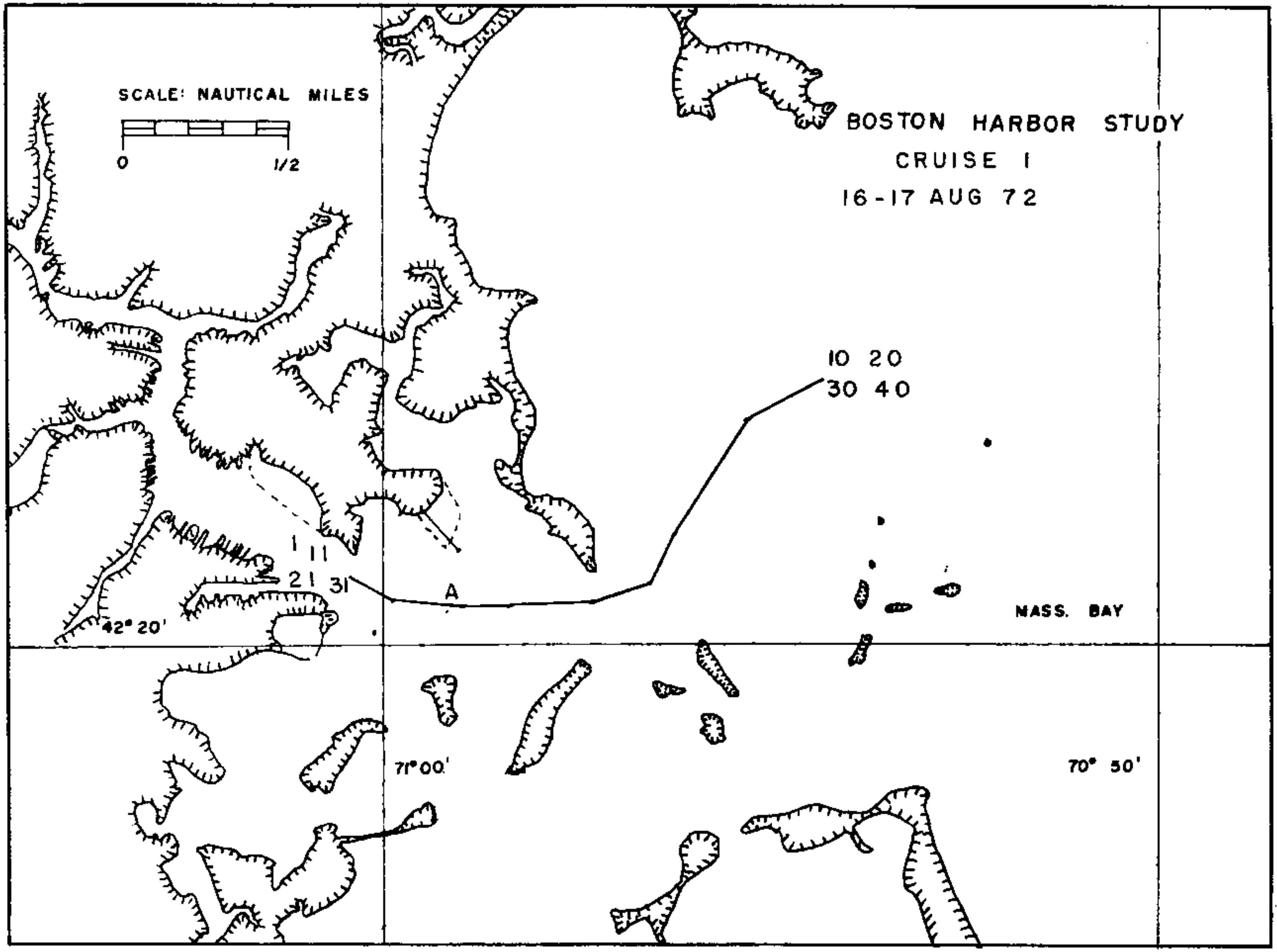


Figure 8 SECTION LOCATIONS . Cruise 1

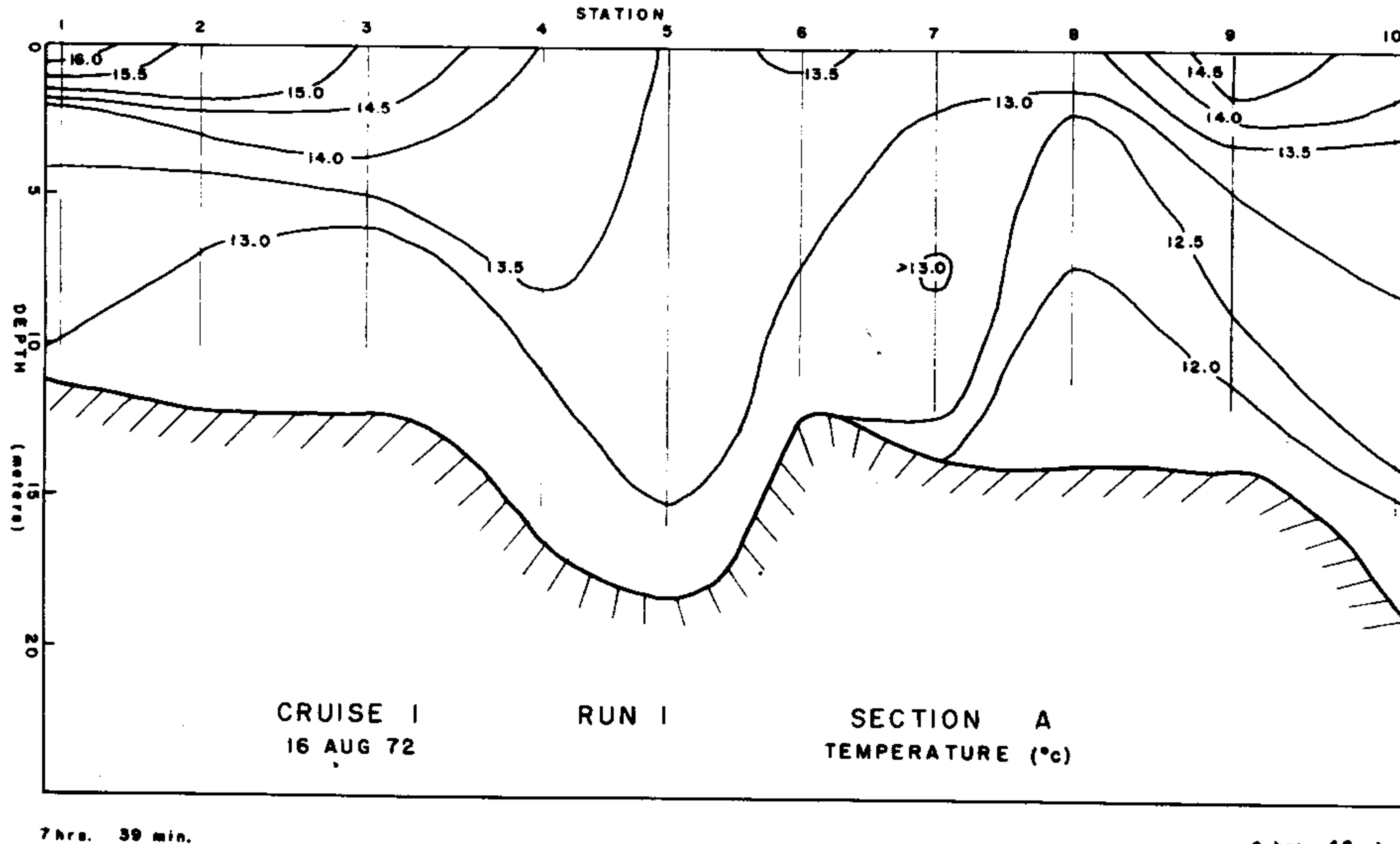


Figure 9 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters
vertical distortion 250:1

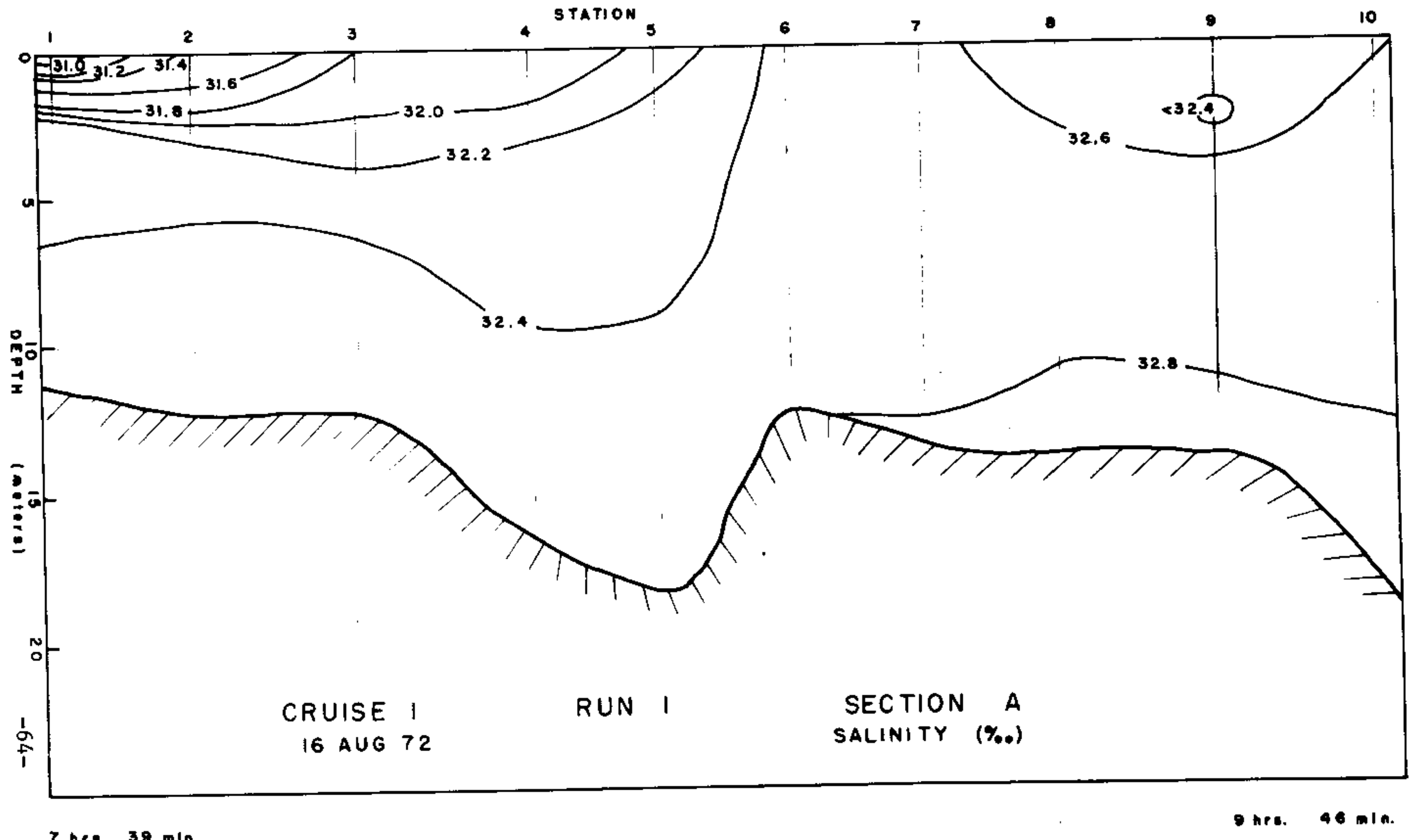


Figure 10 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters
vertical distortion 250:1

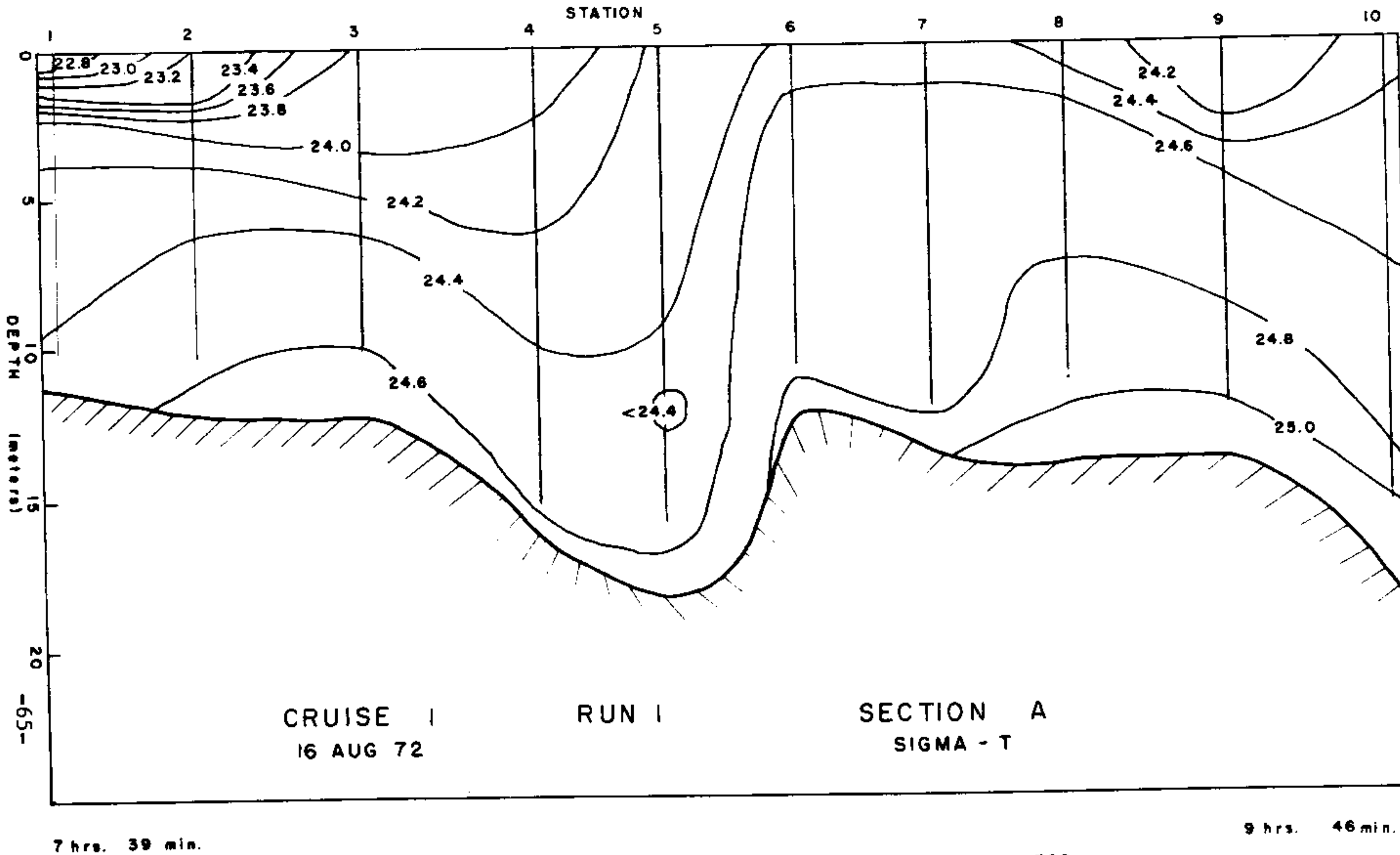


Figure 11 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters vertical distortion 250:1

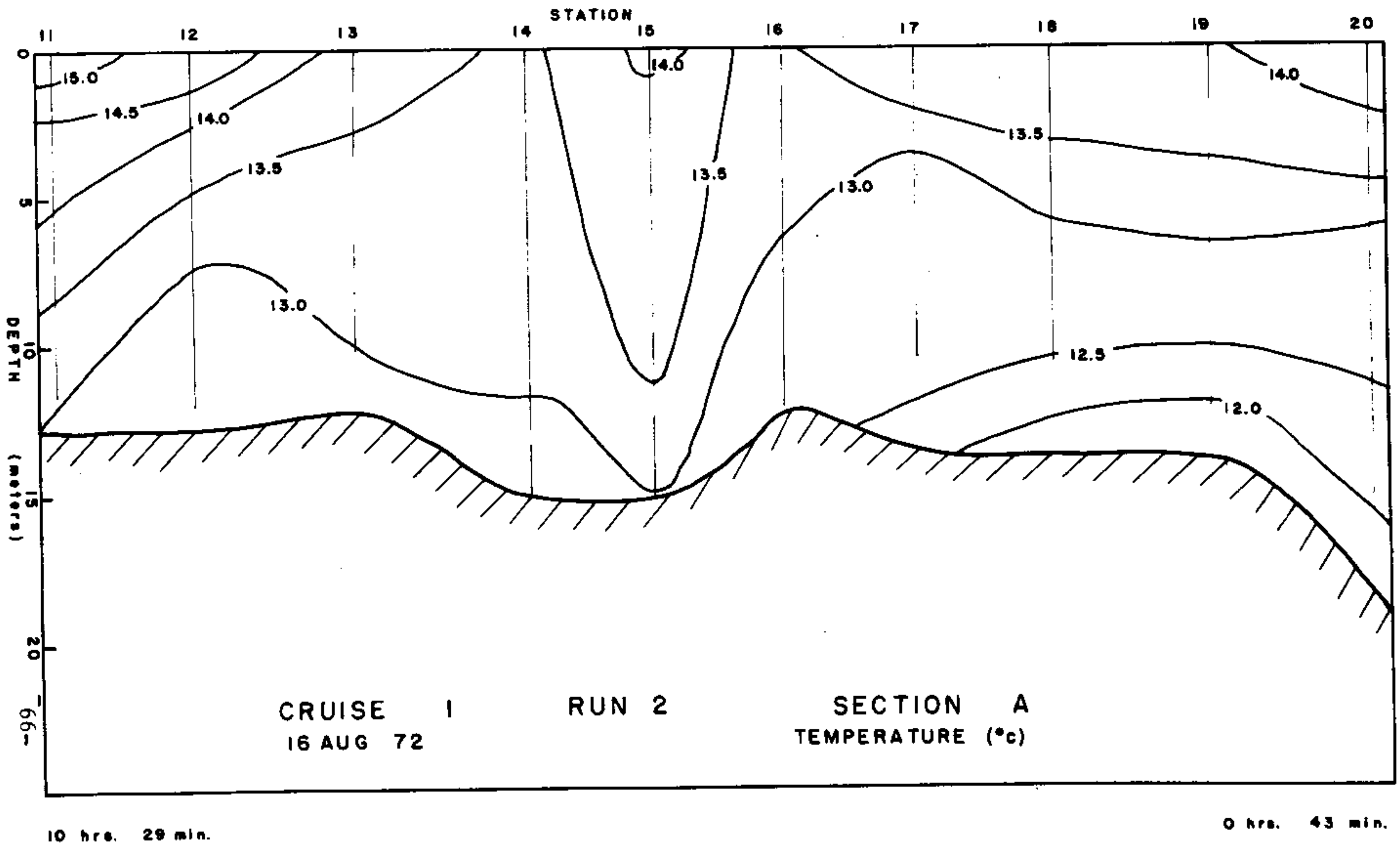


Figure 12 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters vertical distortion 250:1

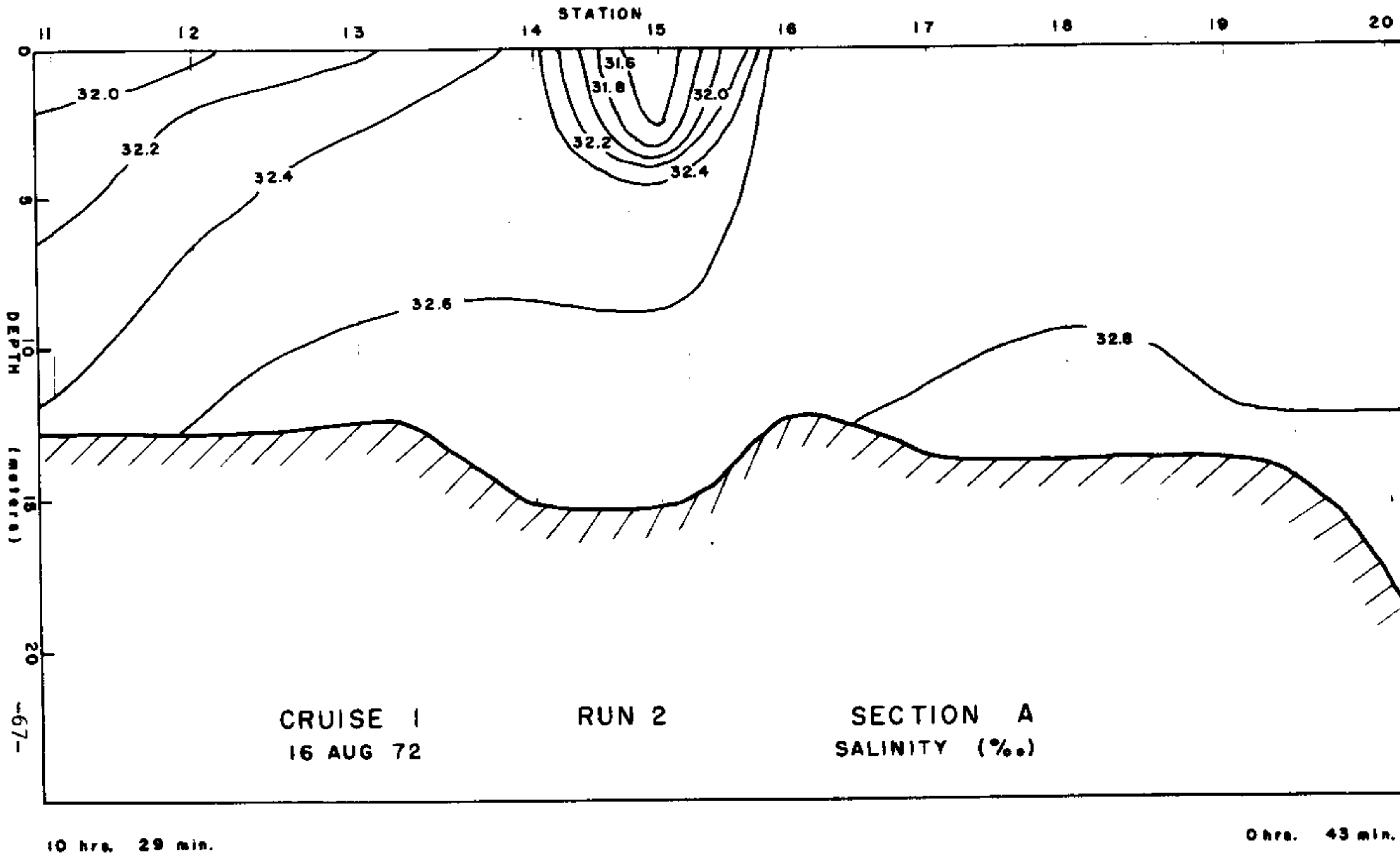


Figure 13 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters
vertical distortion 250:1

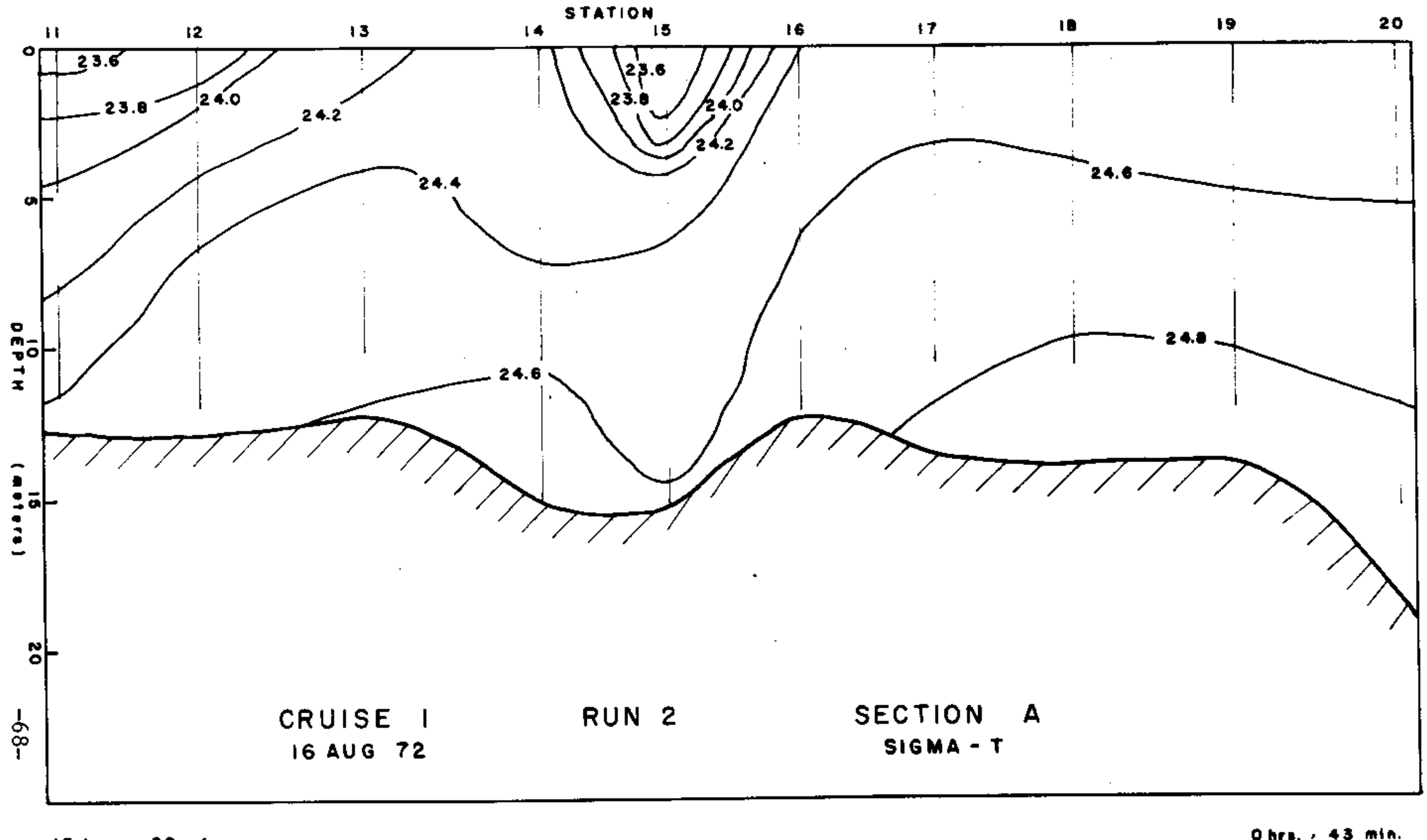
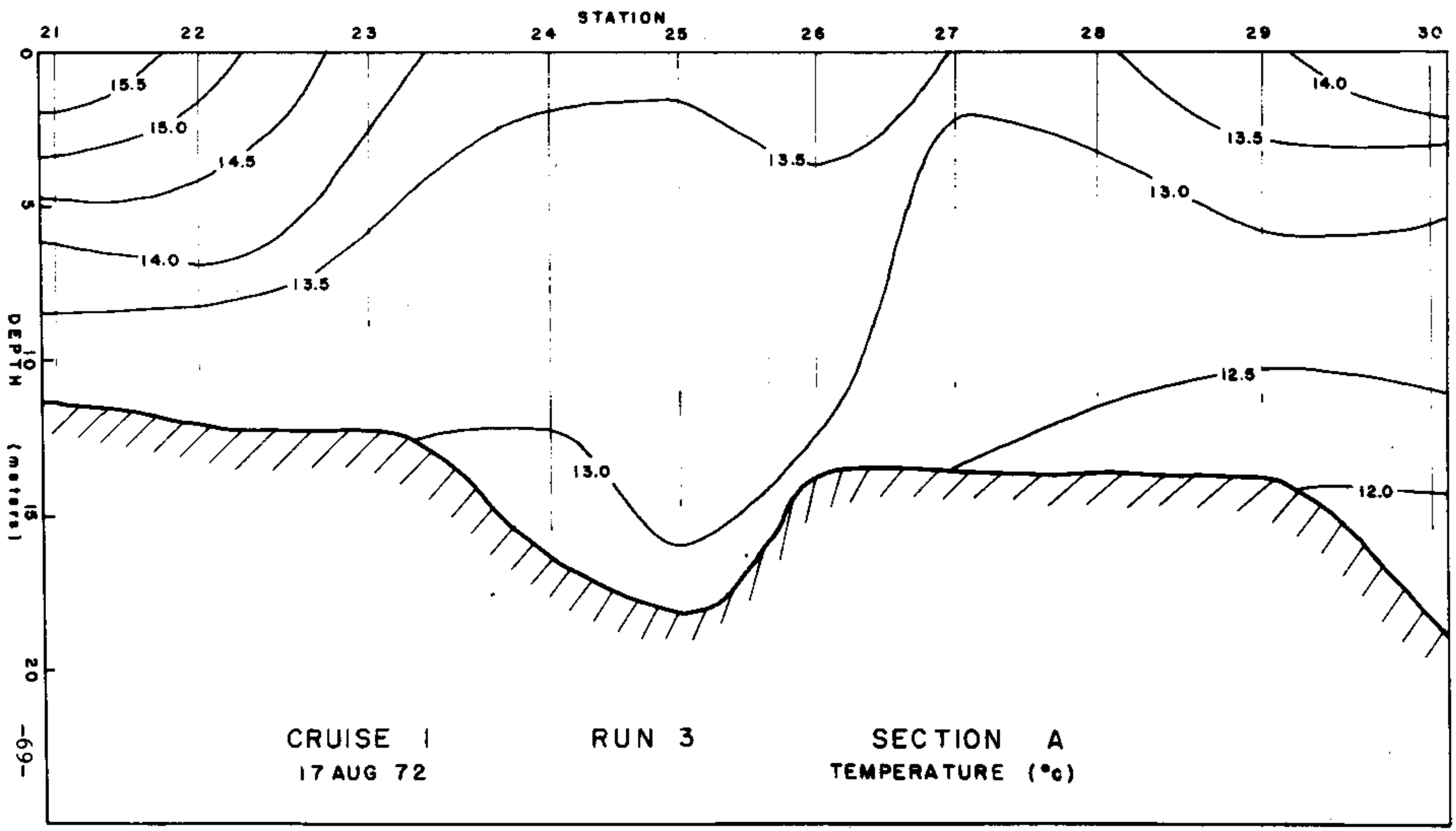


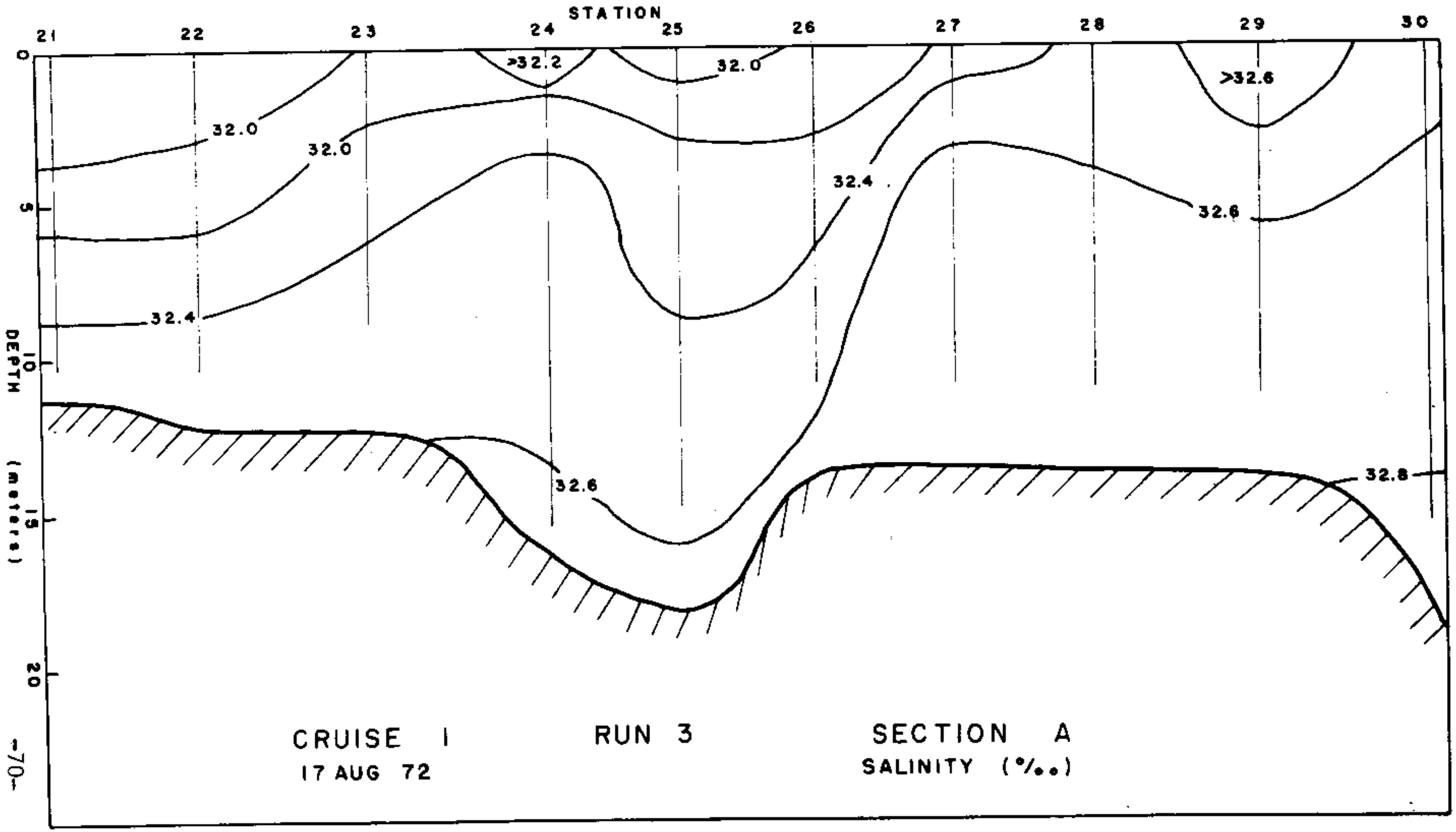
Figure 14 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters vertical distortion 250:1



2 hrs. 40 min.

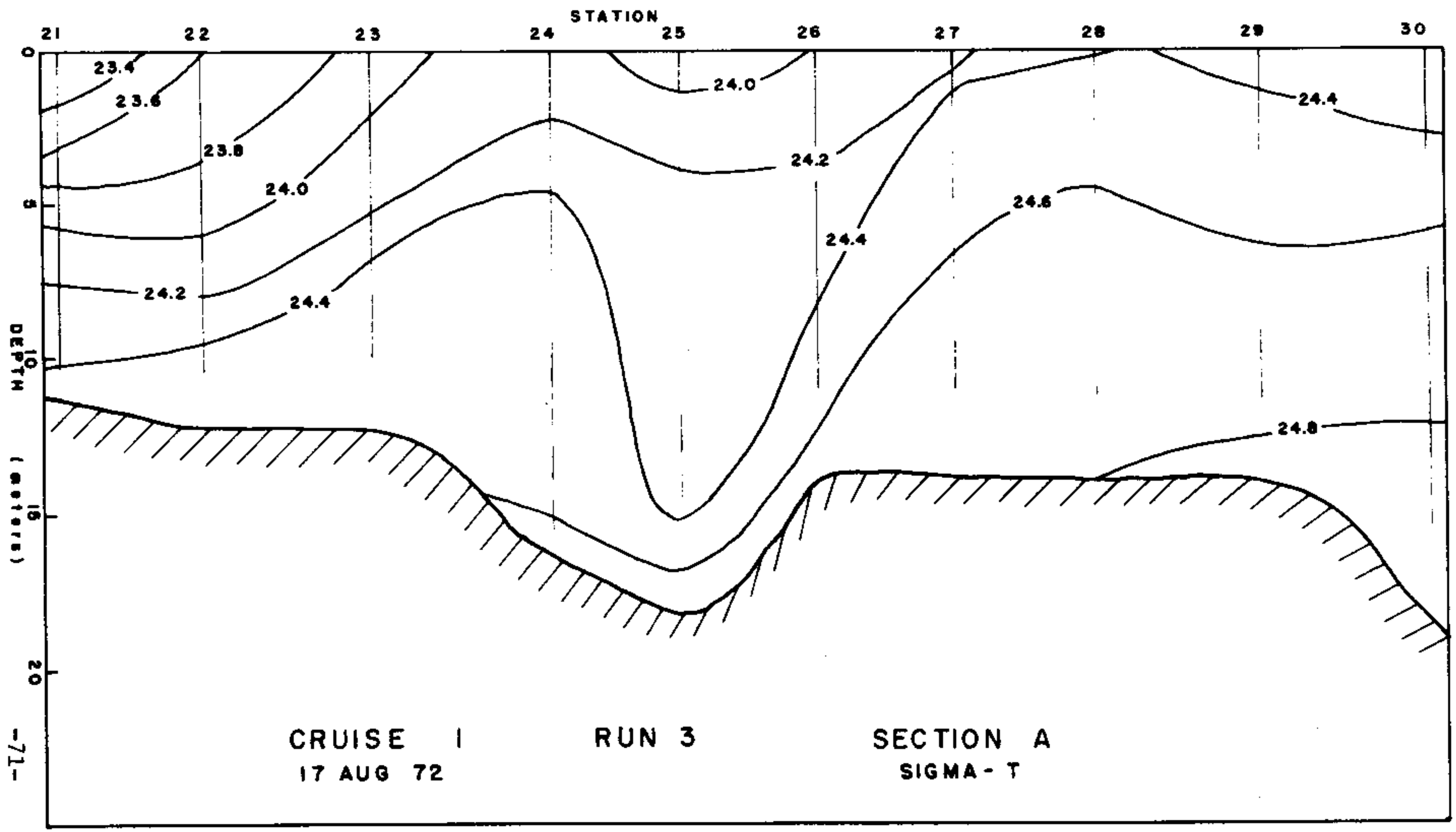
3 hrs. 46 min.

Figure 15 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters vertical distortion 250:1



2 hrs. 40 min. 3 hrs. 46 min.

Figure 16 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters vertical distortion 250:1



2 hrs. 40 min. 3 hrs. 46 min.

Figure 17 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters. vertical distortion 250:1

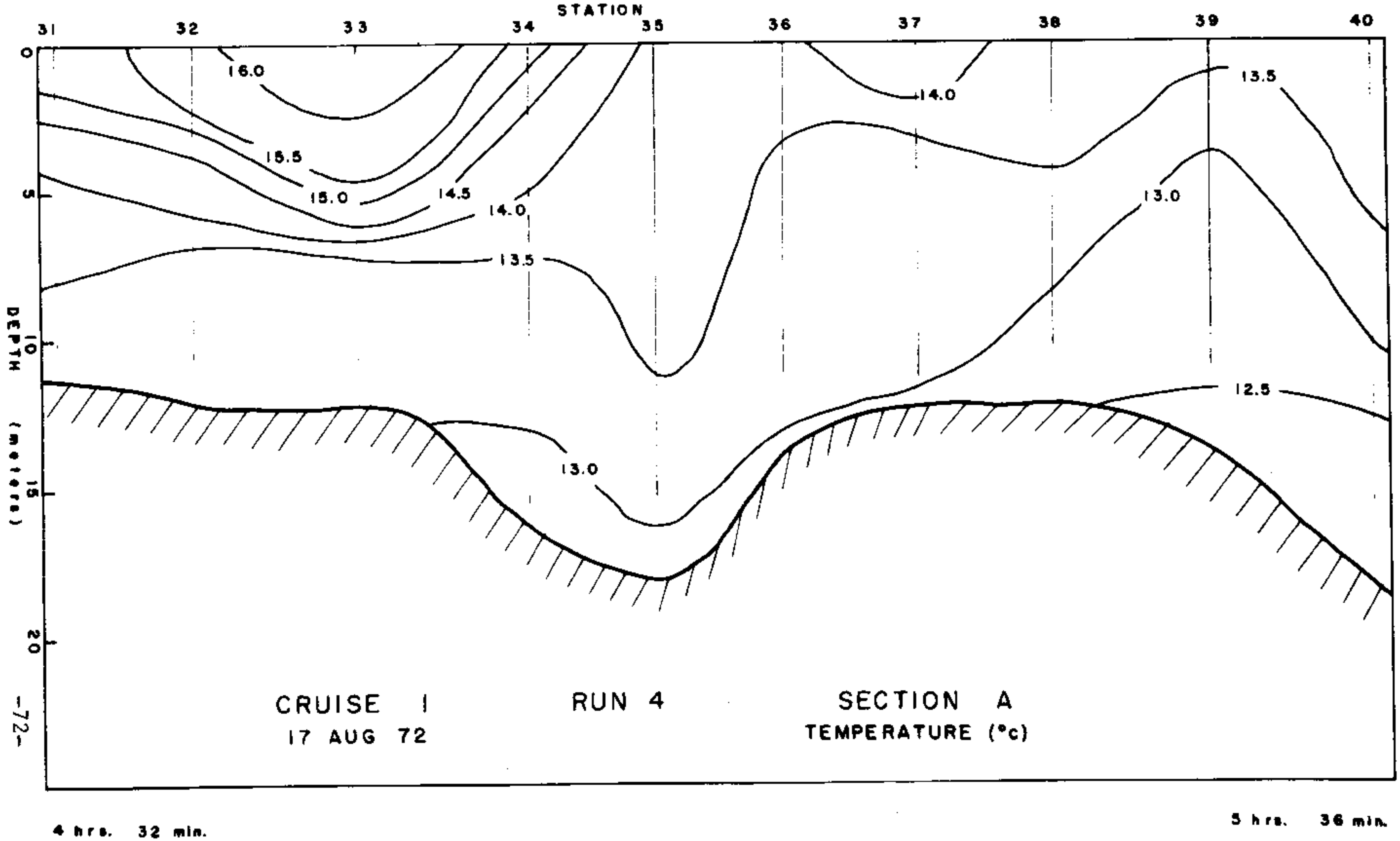


Figure 18 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters vertical distortion 250:1

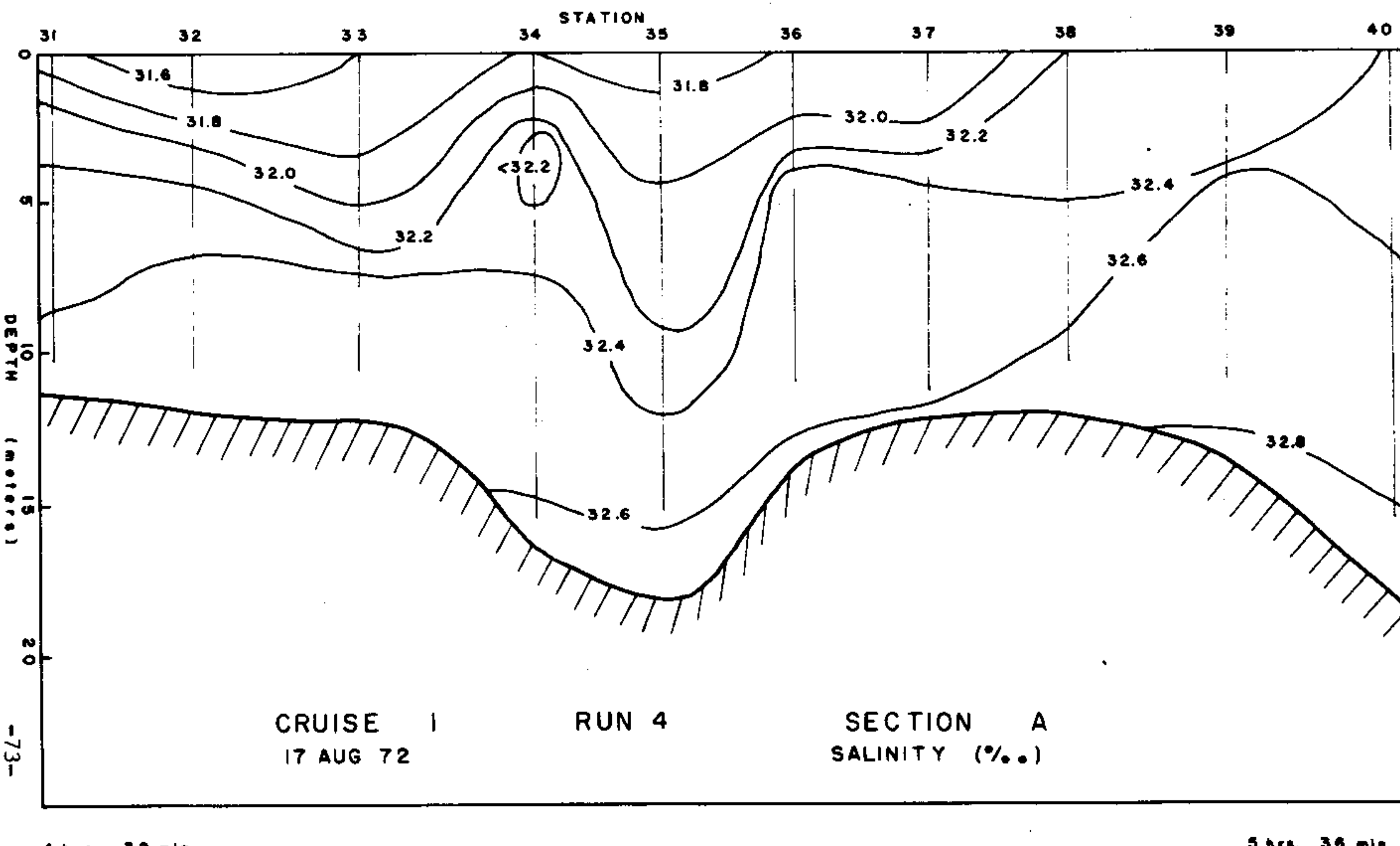


Figure 19 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters
vertical distortion 250:1

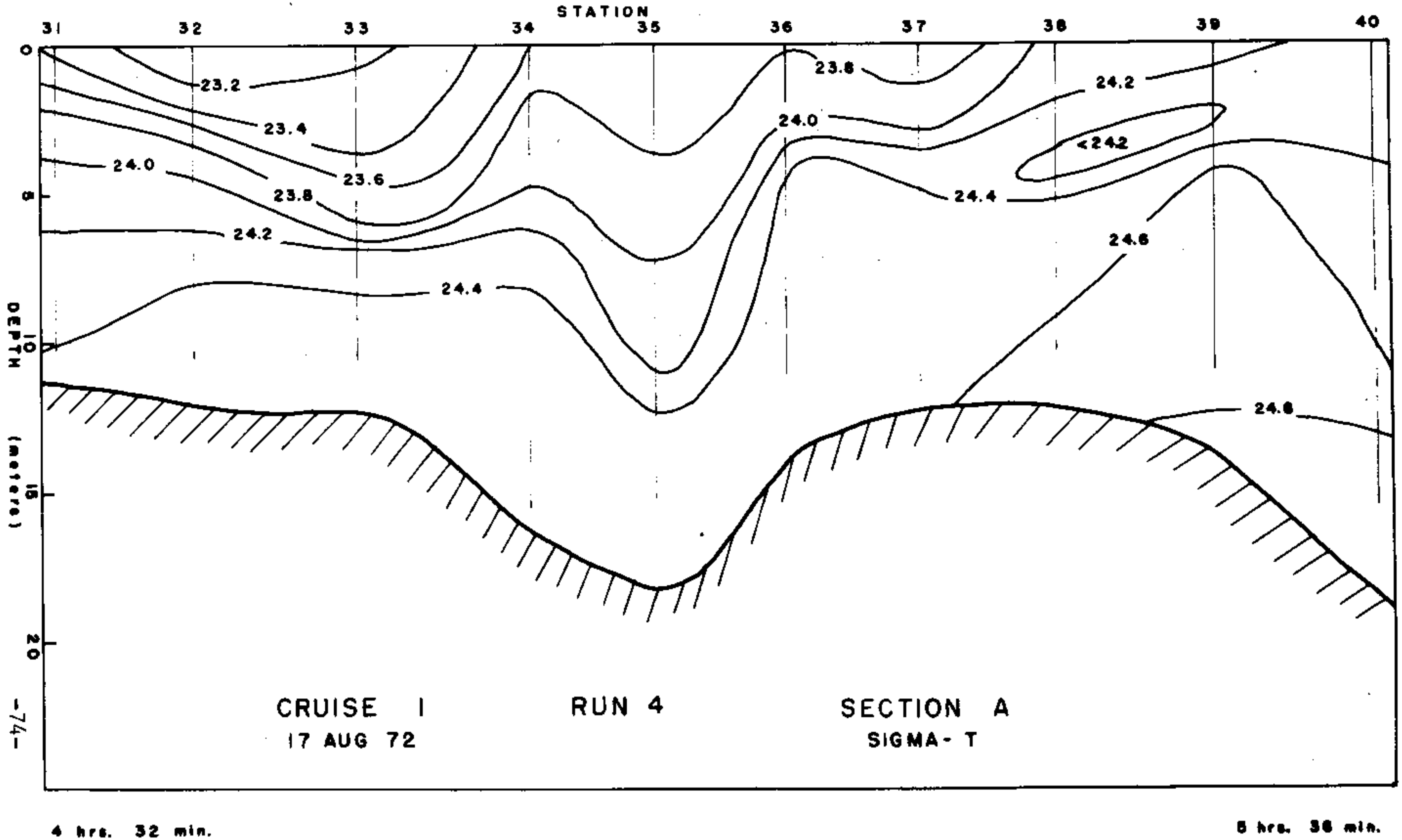


Figure 20 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters
vertical distortion 250:1

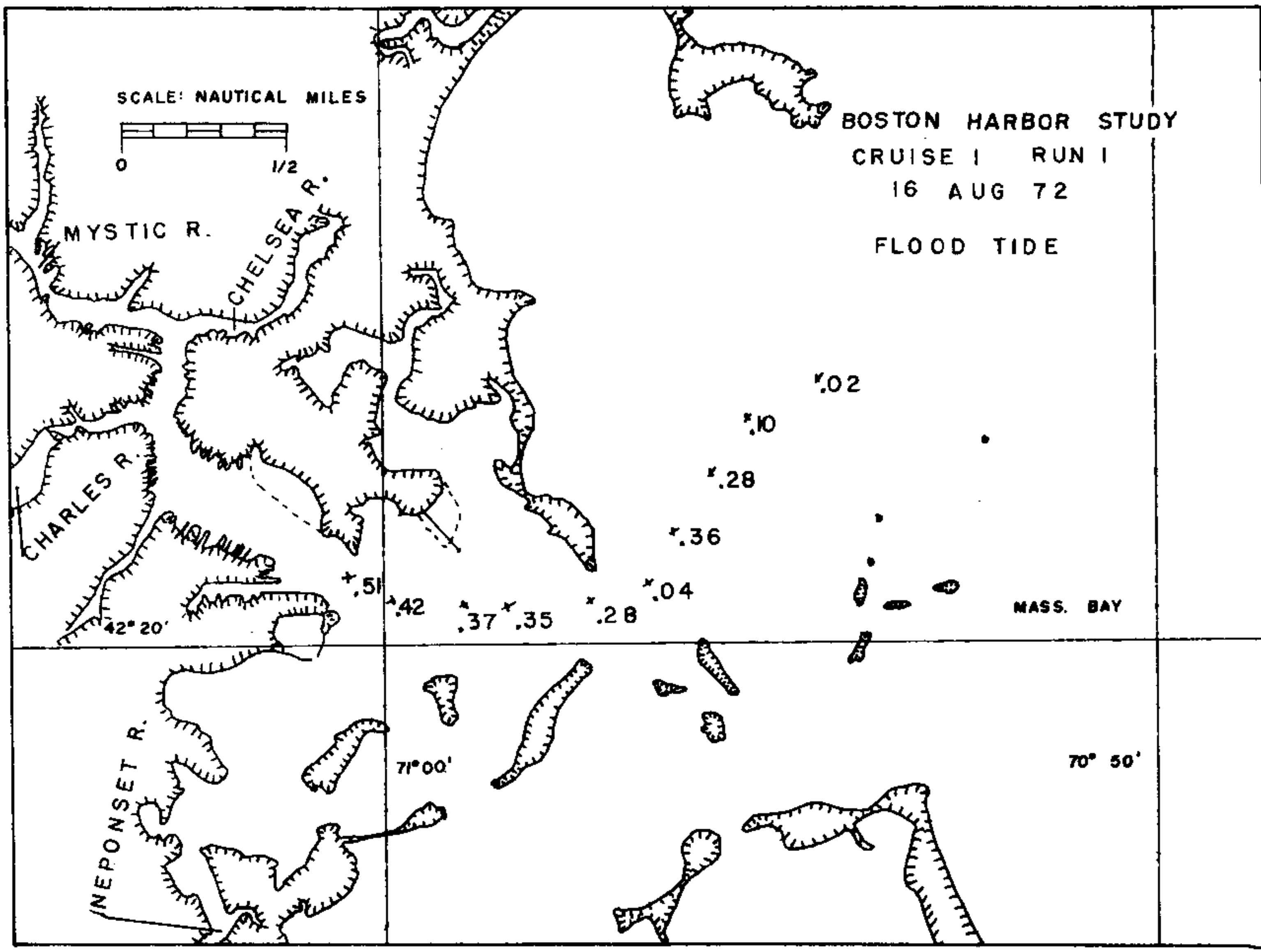


Figure 21 SURFACE NITRITES in μgm. at m./l.

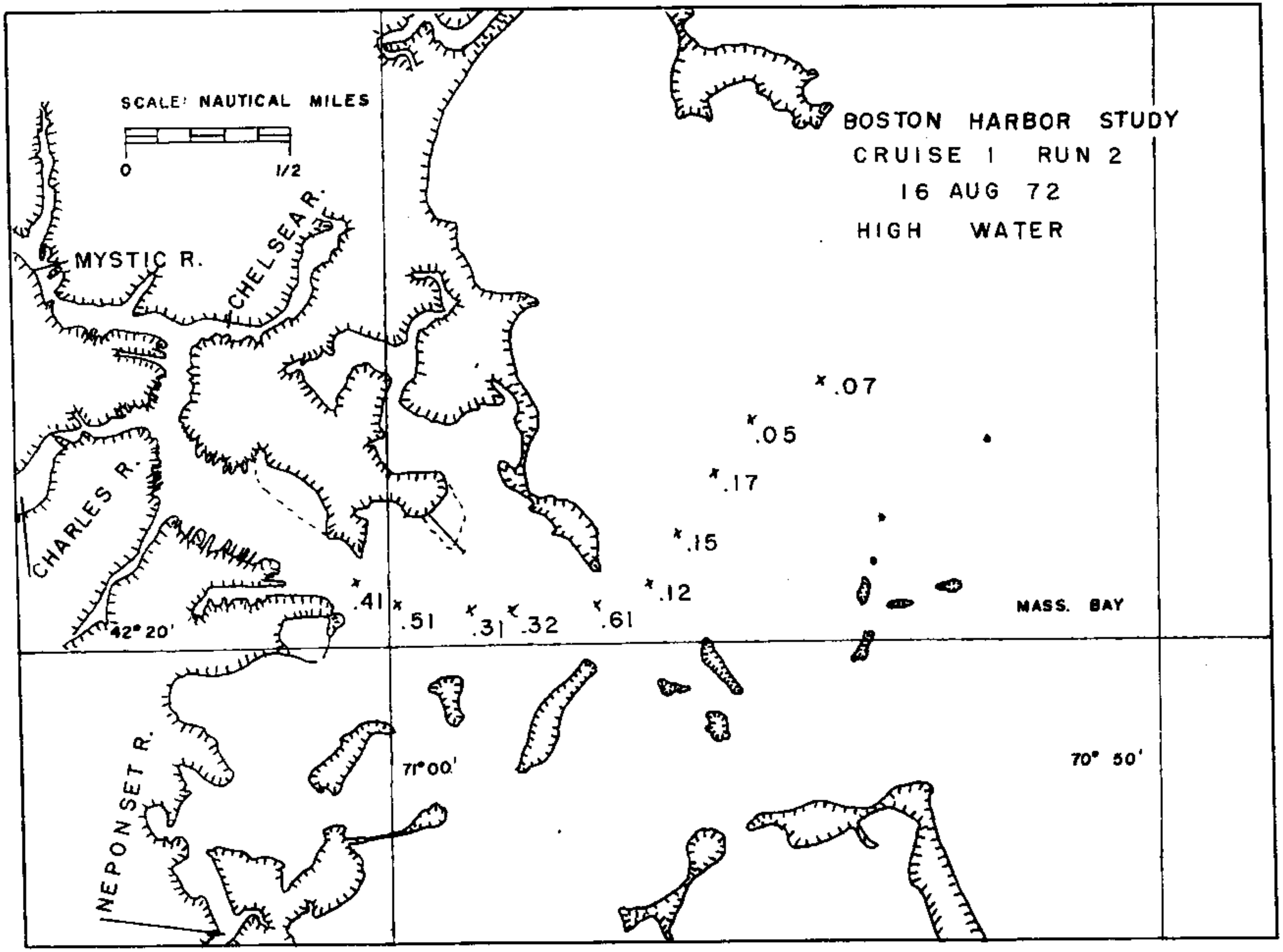


Figure 22 SURFACE NITRITES in μgm. atm. / l.

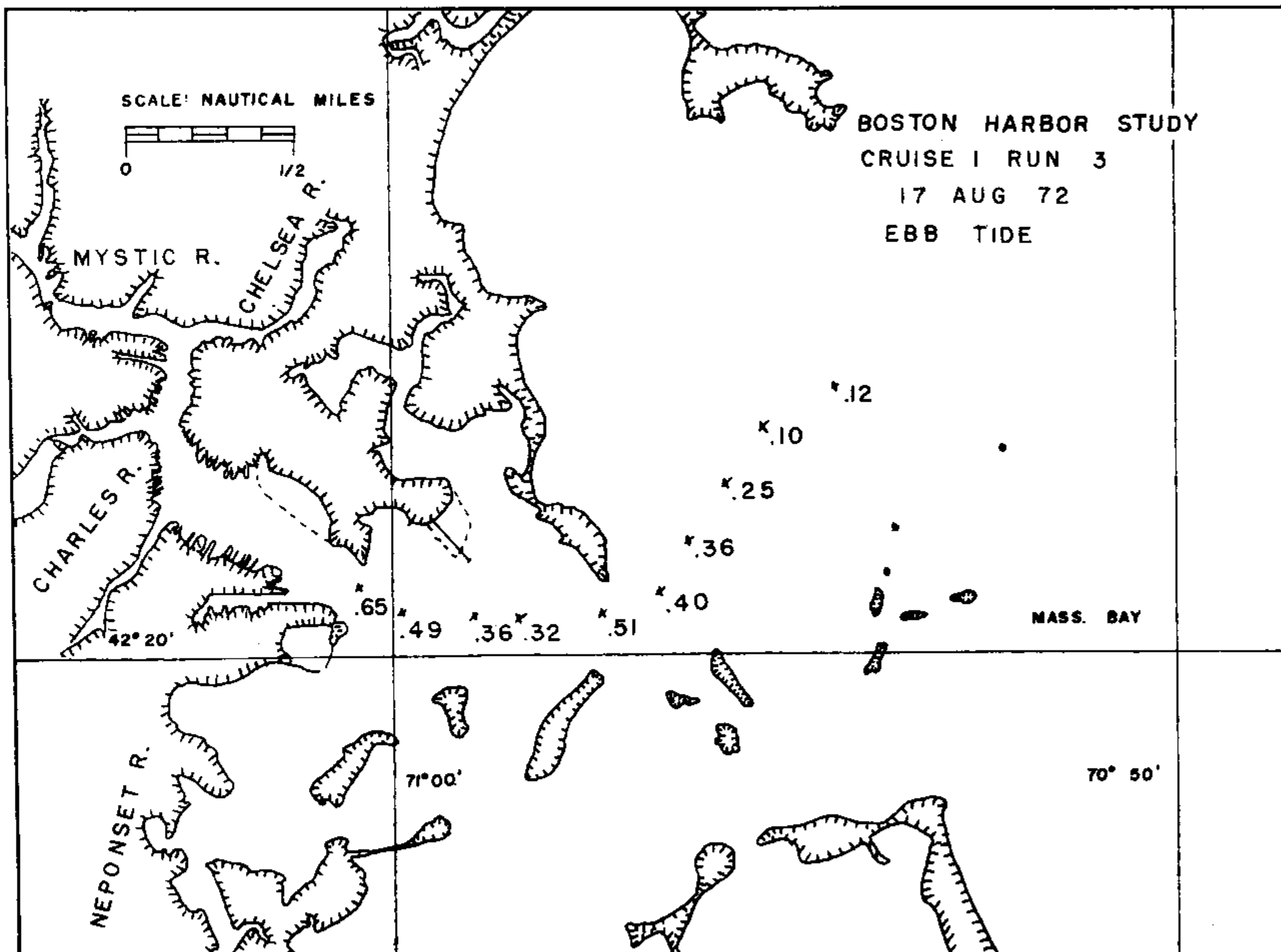


Figure 23 SURFACE NITRITES in μgm. atm. / l.

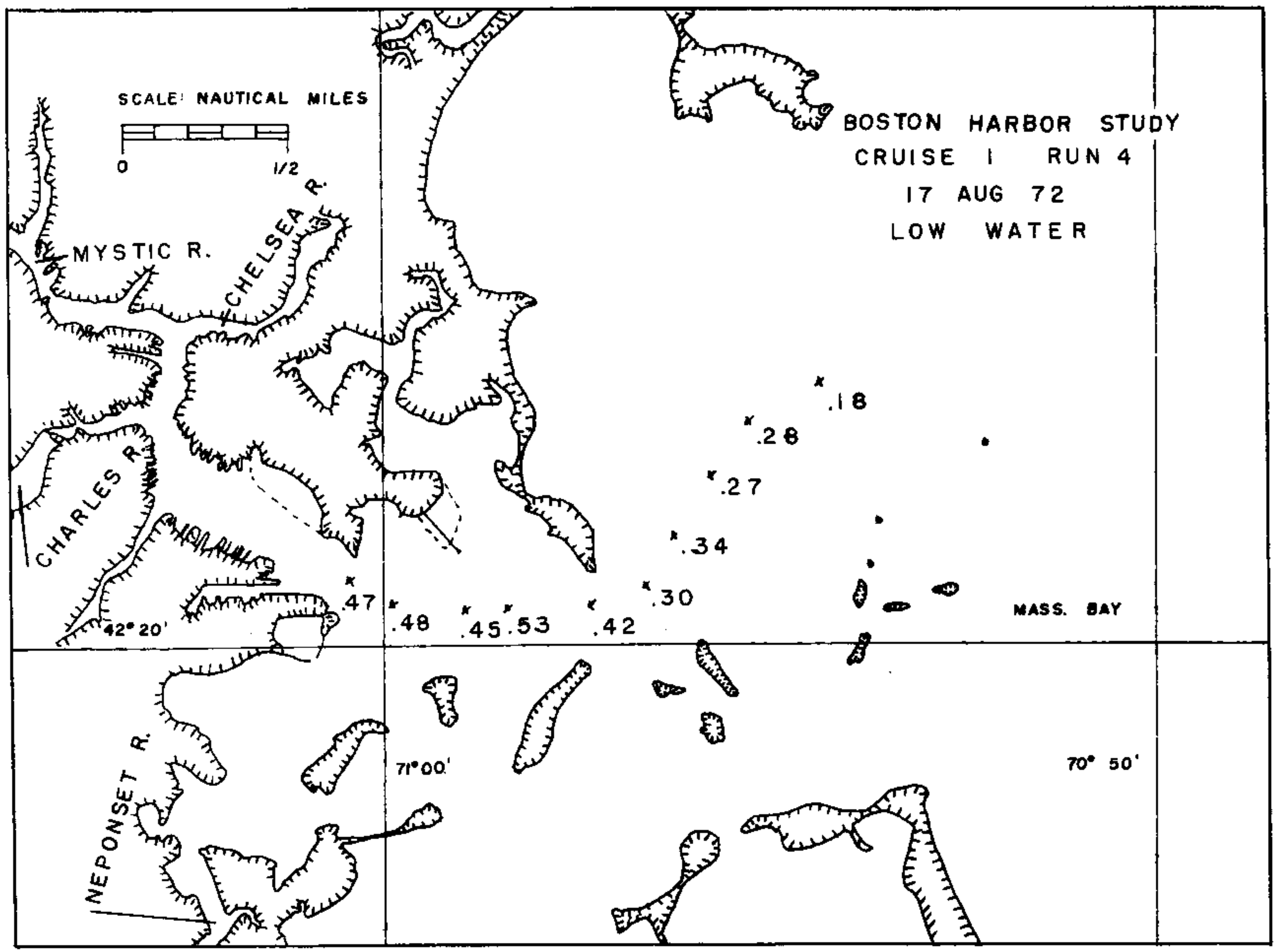


Figure 24 SURFACE NITRITES in μgm. atm./l.

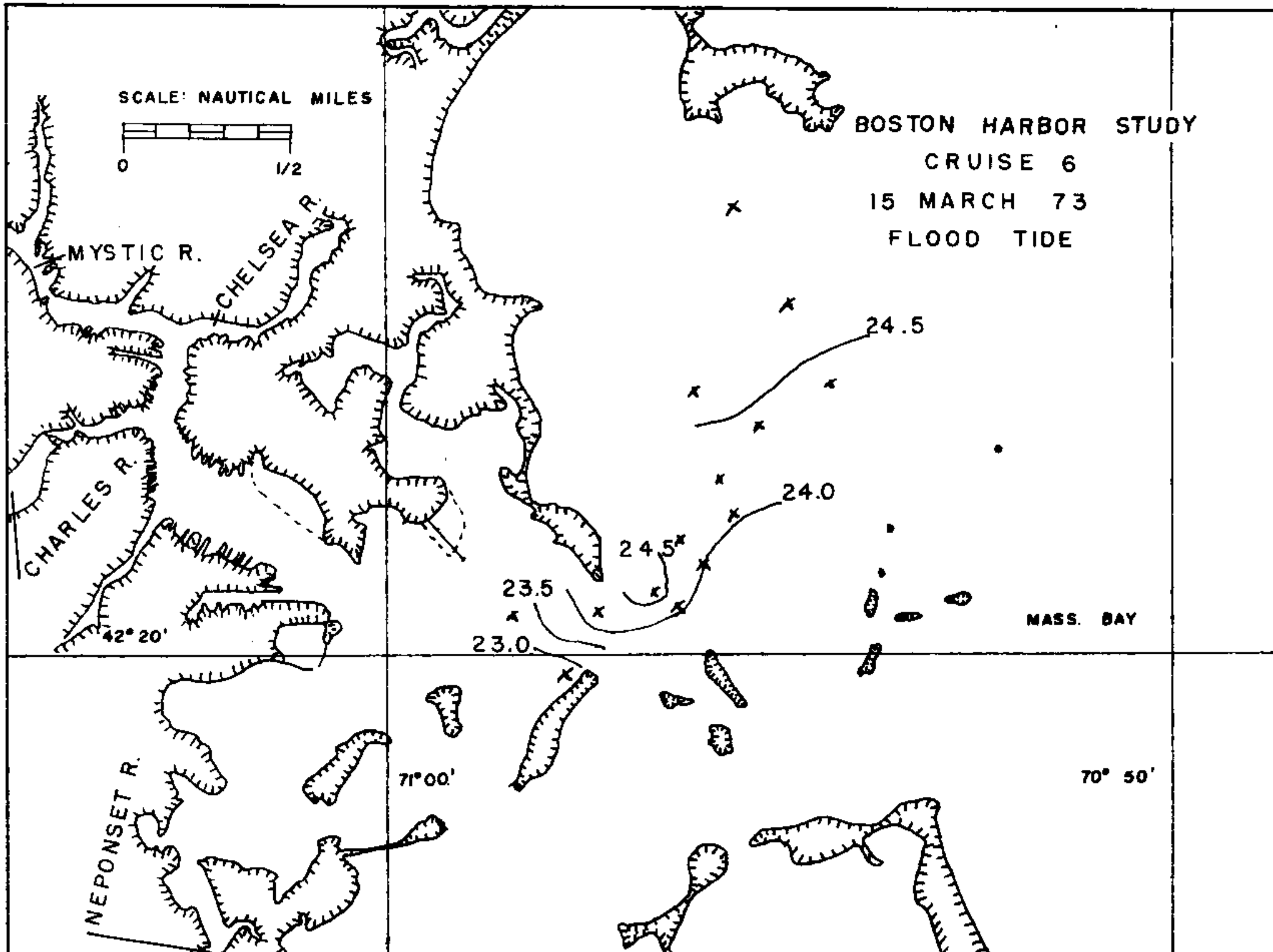


Figure 25 SURFACE SIGMA-T

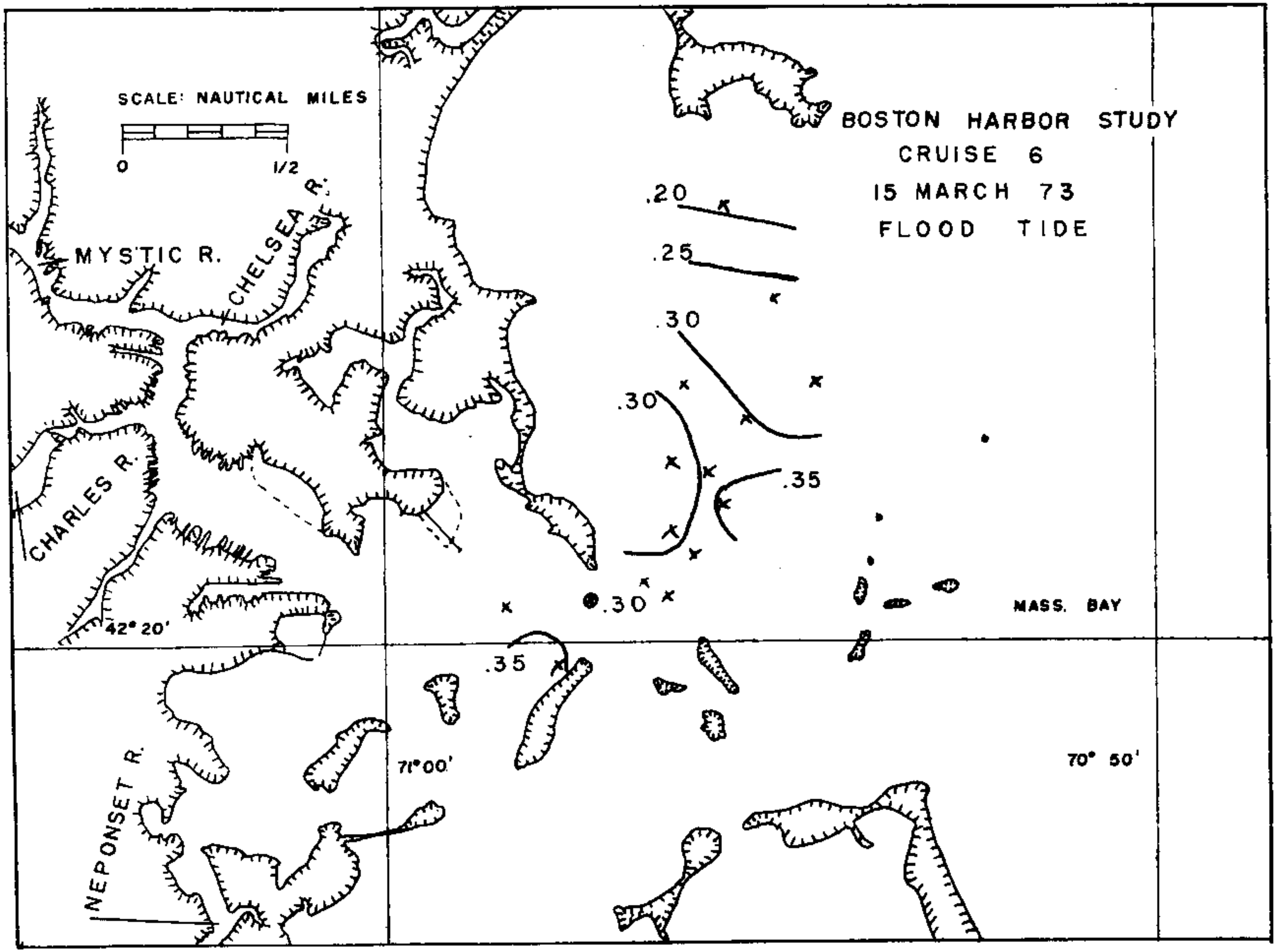


Figure 26 SURFACE NITRITES in μgm. atm. / l.

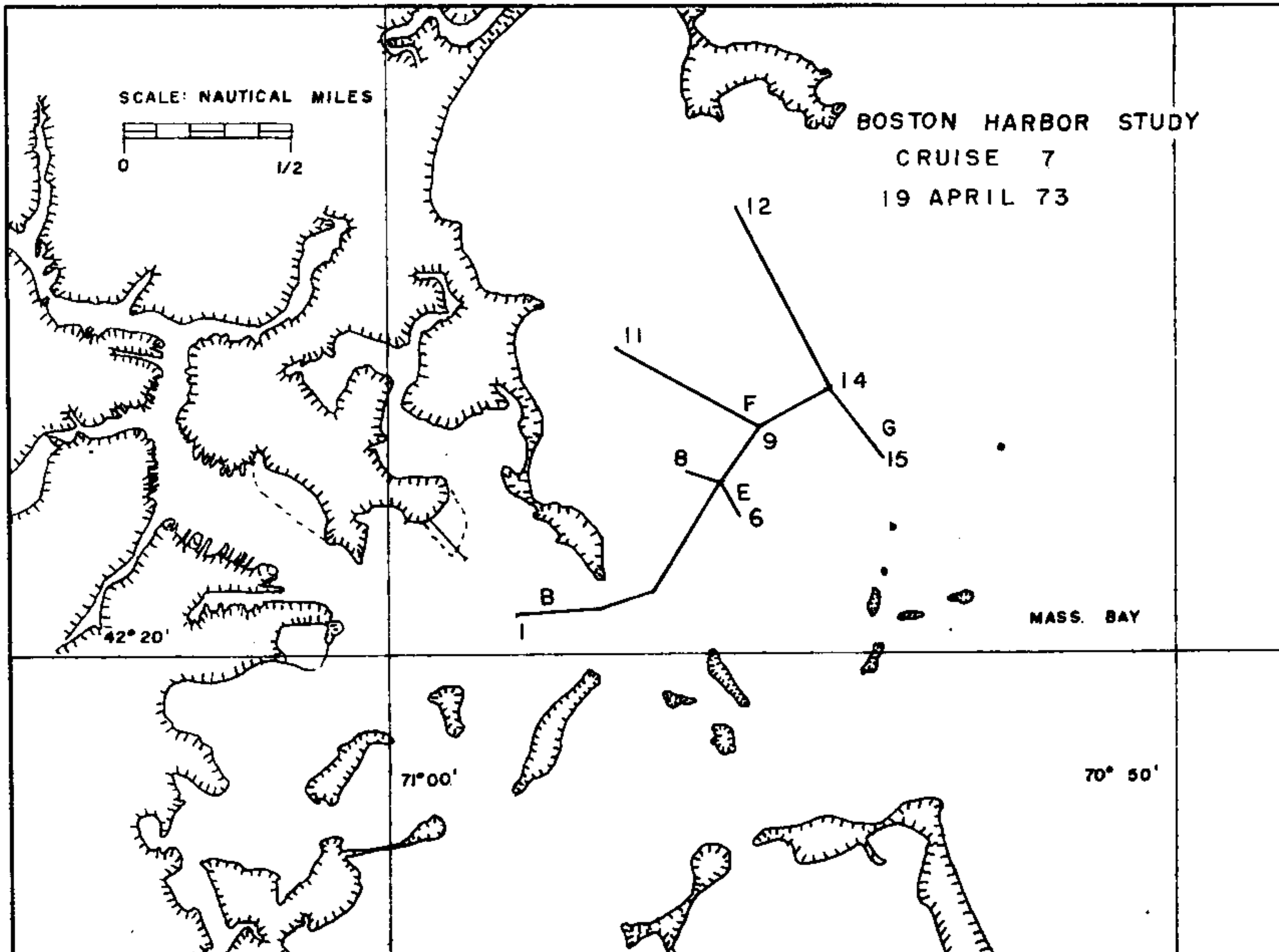
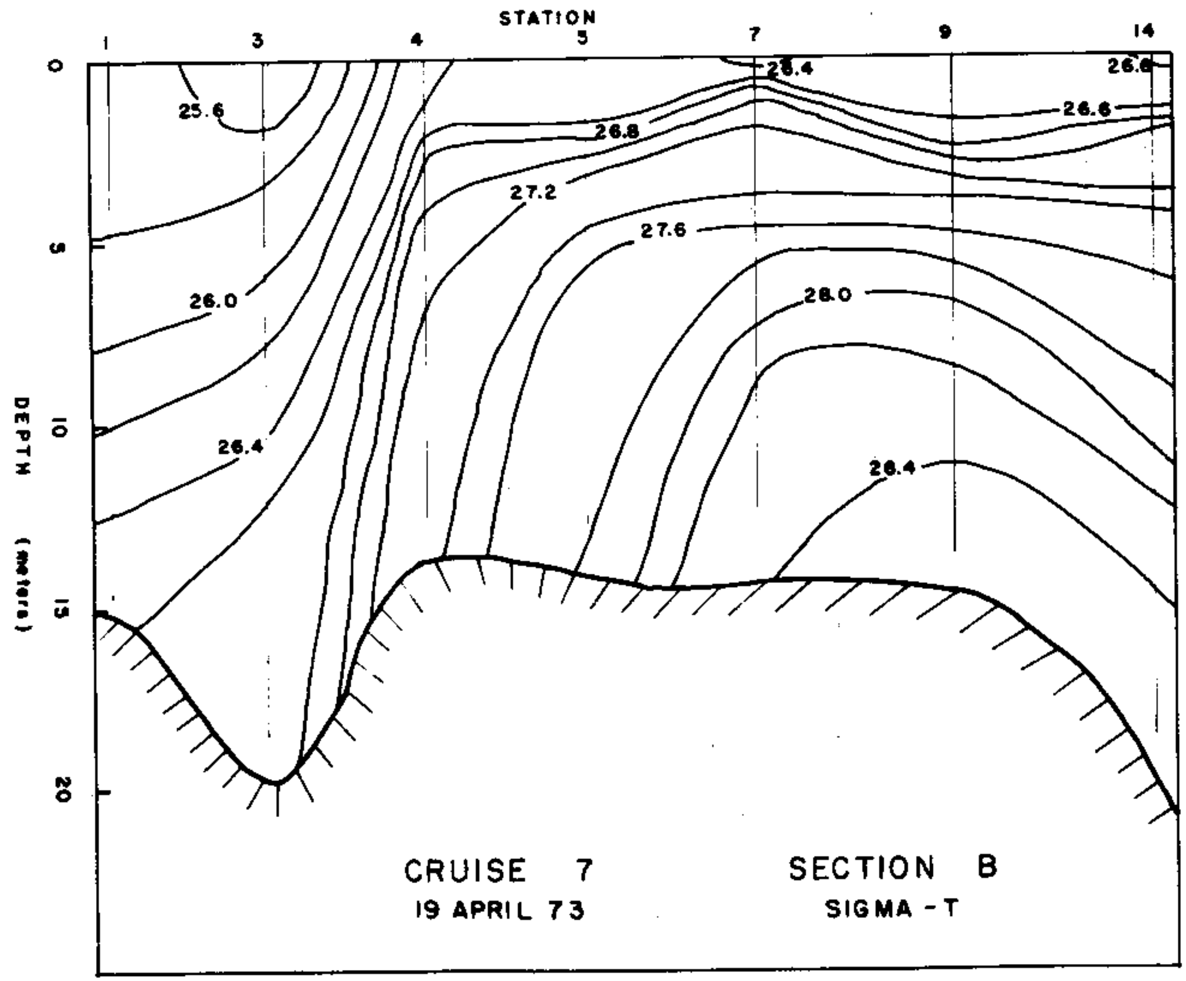


Figure 27 SECTION LOCATIONS Cruise 7



11 hrs. 53 min. 1 hr. 26 min.

Figure 28 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters vertical distortion 250:1

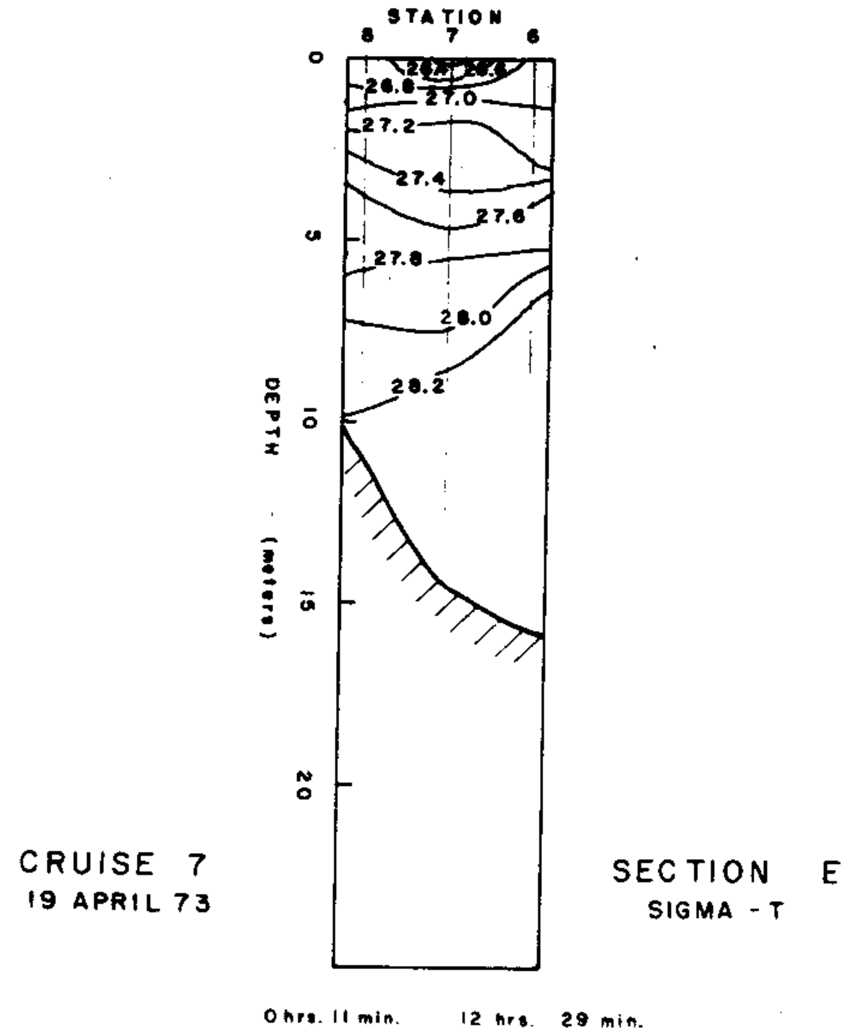
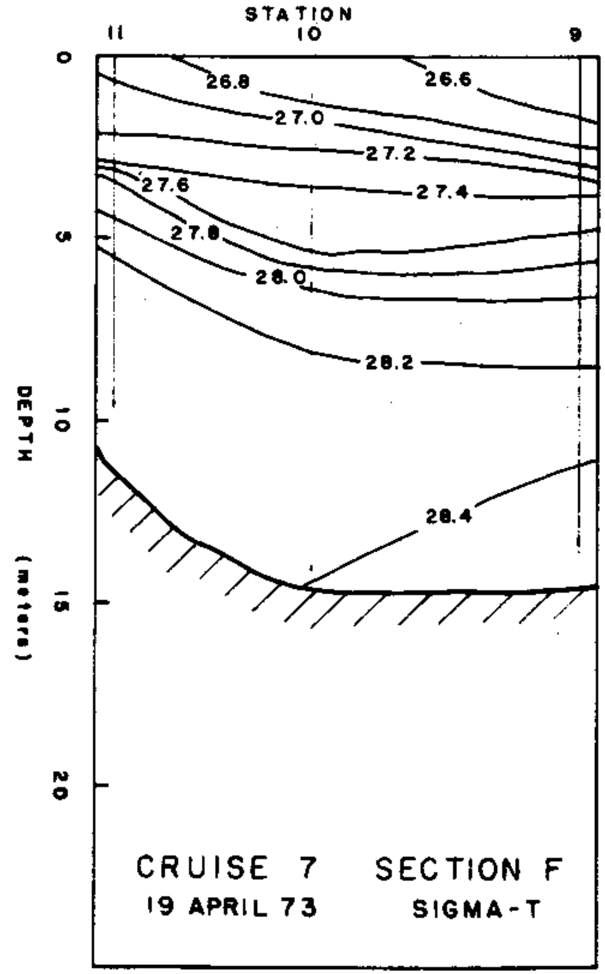


Figure 29 Times refer to hours after high water, Boston. Scale: 1 cm = 500 meters vertical distortion 250:1



0 hrs. 42 min. 0 hrs. 21 min.

Figure 30 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters
vertical distortion 250:1

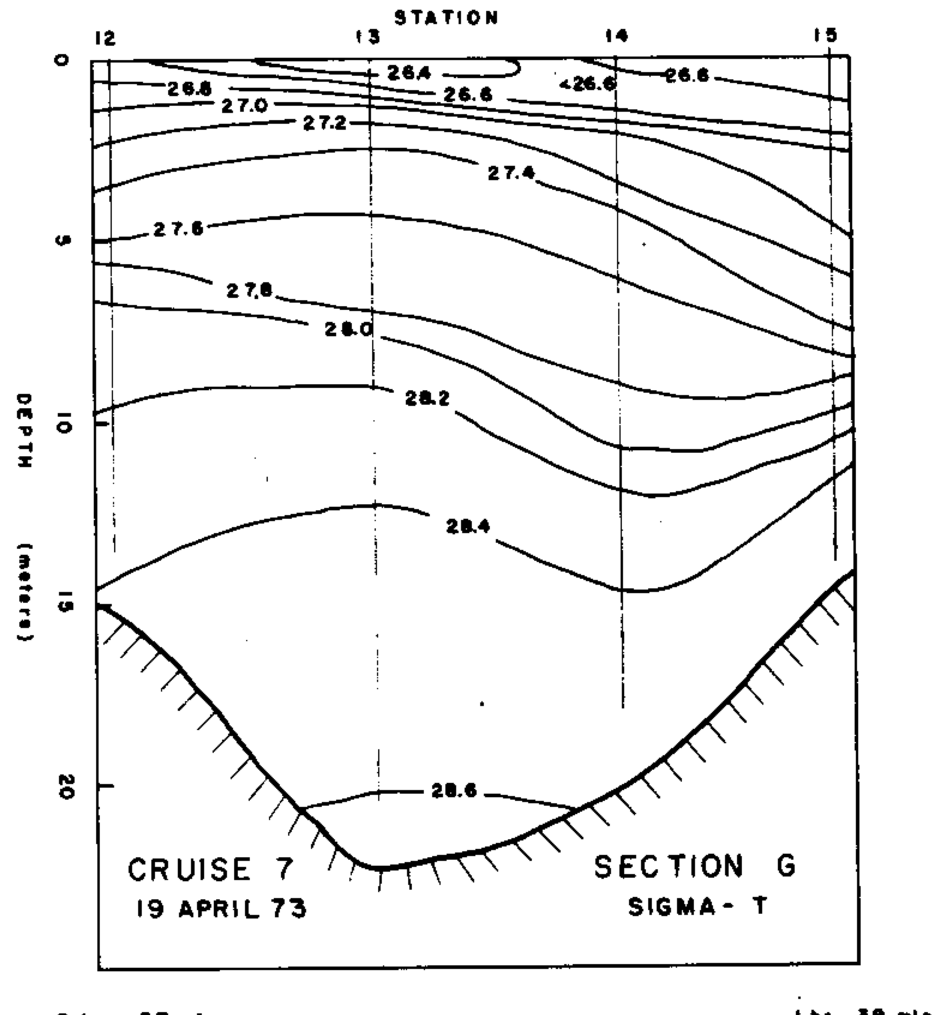


Figure 31 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters vertical distortion 250:1

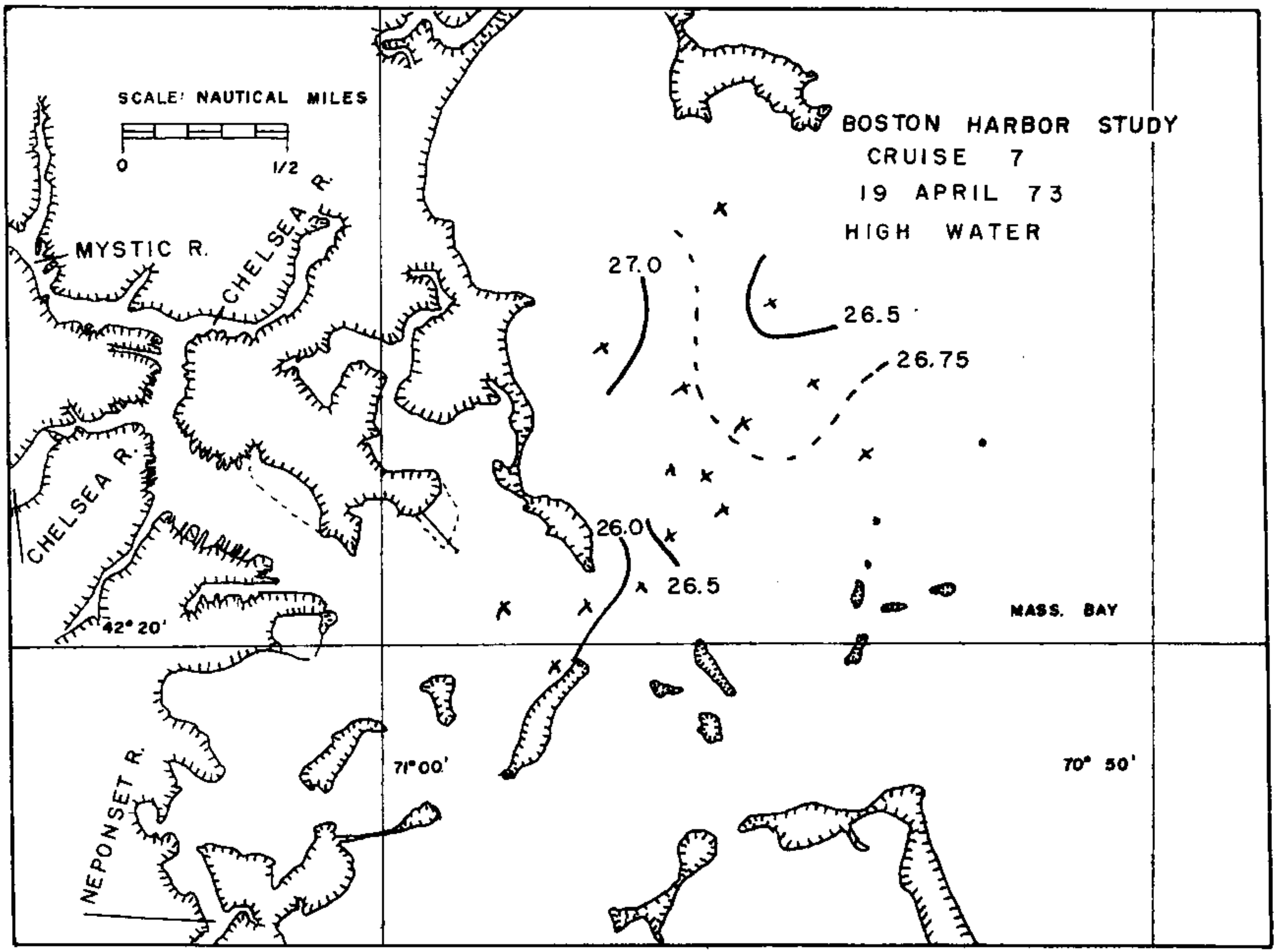


Figure 32 1.0 METER SIGMA - T

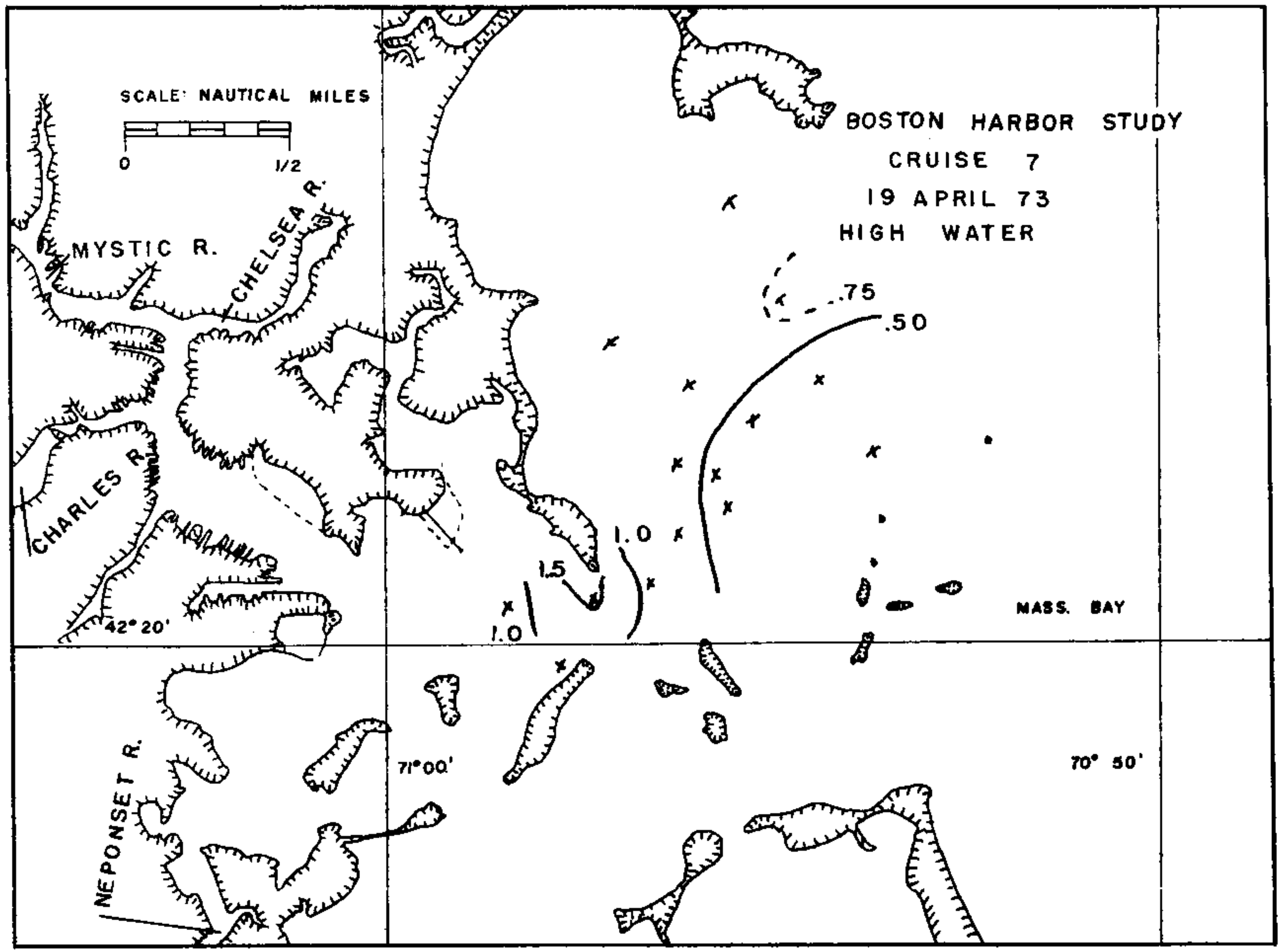


Figure 33 SURFACE NITRITES PLUS NITRATES in μgm.atm./l.

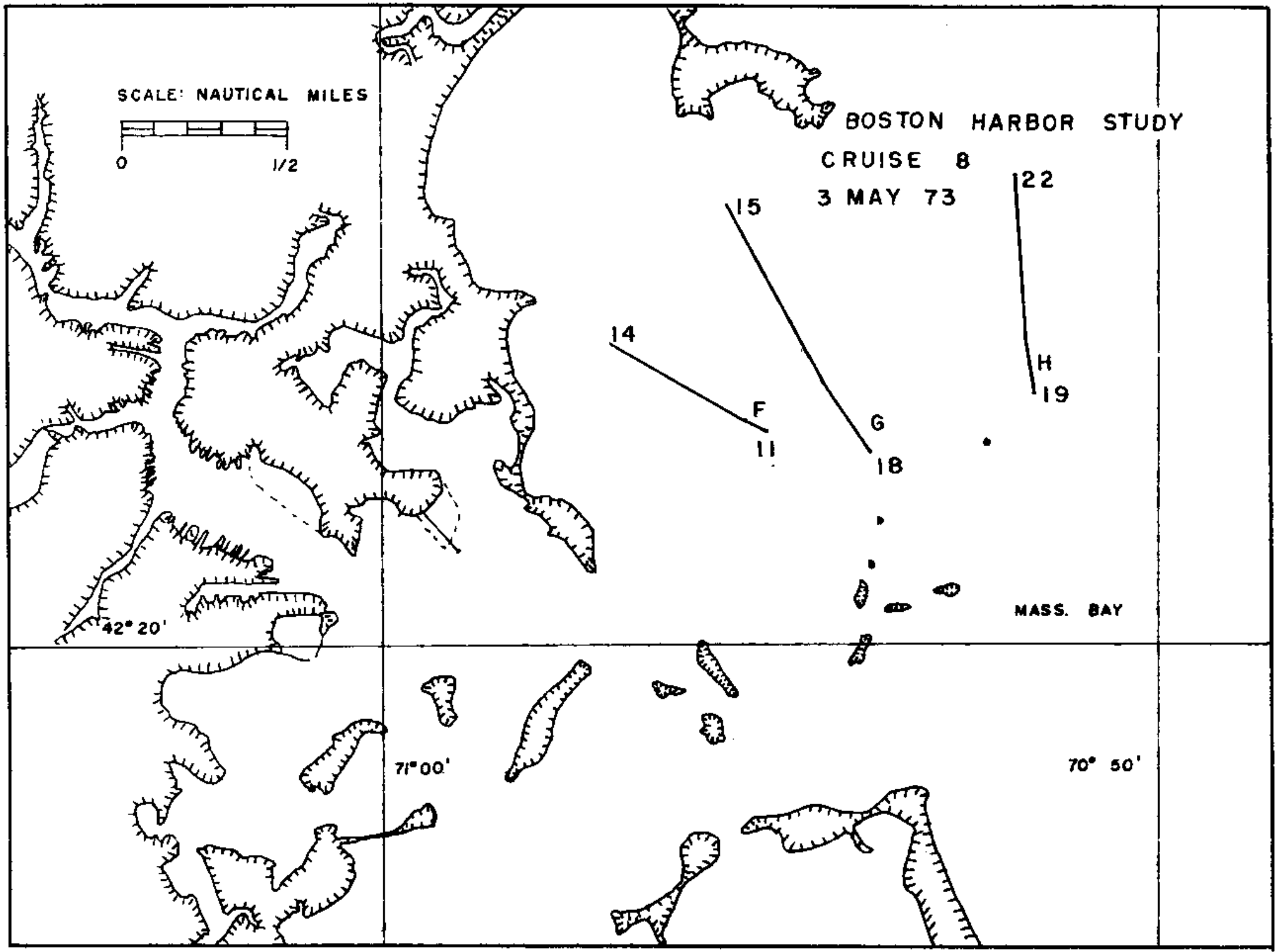


Figure 34 SECTION LOCATIONS. Cruise 8

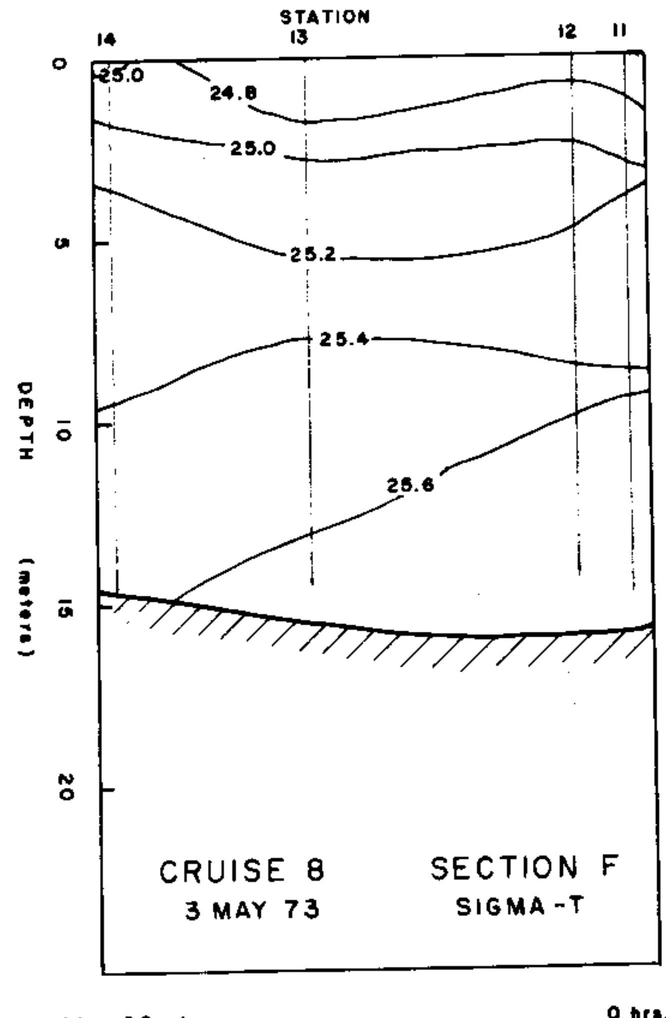


Figure 35 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters vertical distortion 250:1

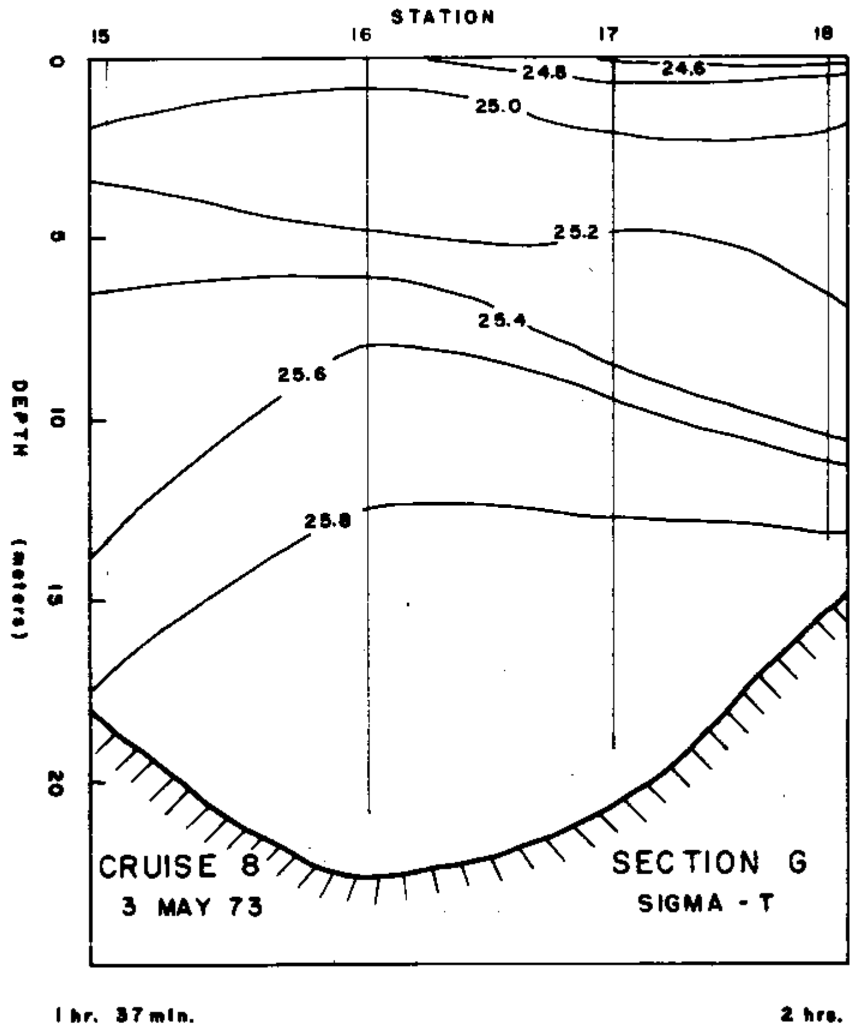


Figure 36 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters vertical distortion 250:1

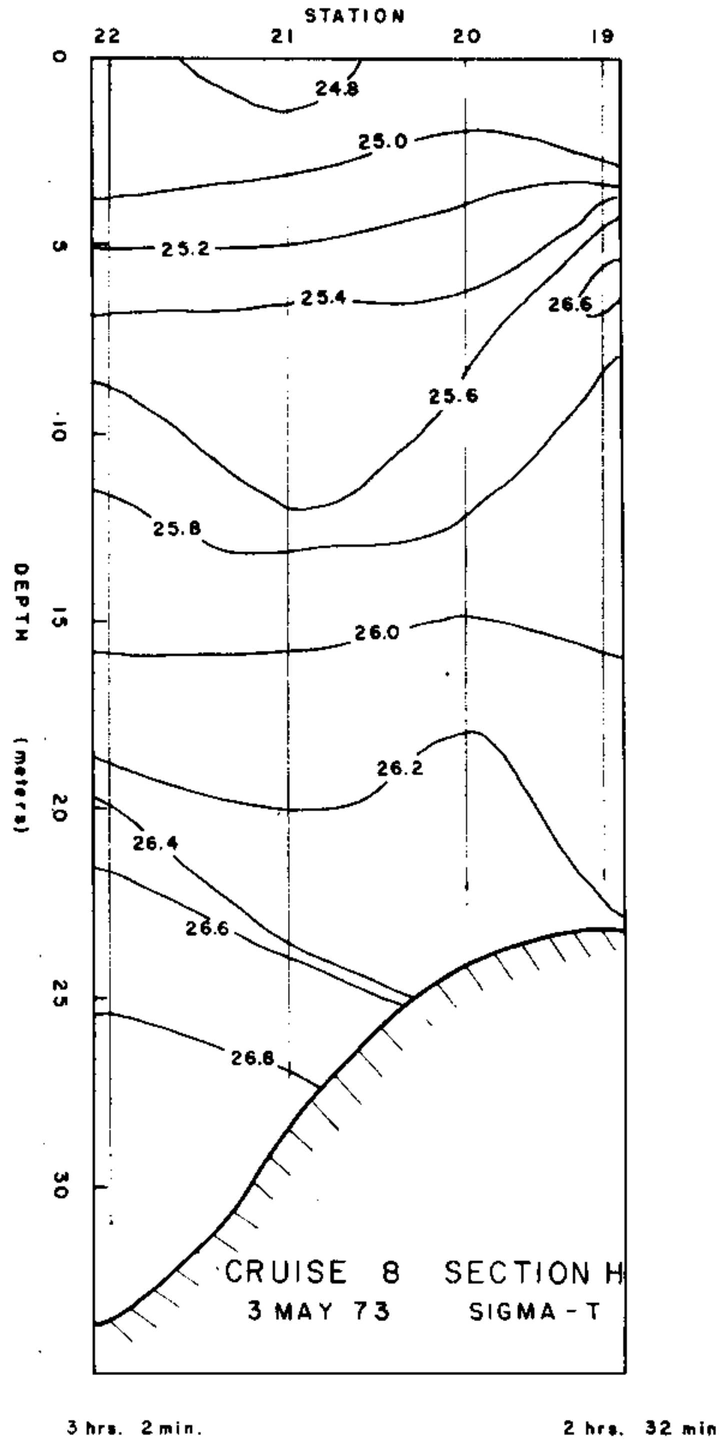


Figure 37 Times refer to hours after high water, Boston.
Scale: 1 cm. = 500 meters, vertical distortion 250:1

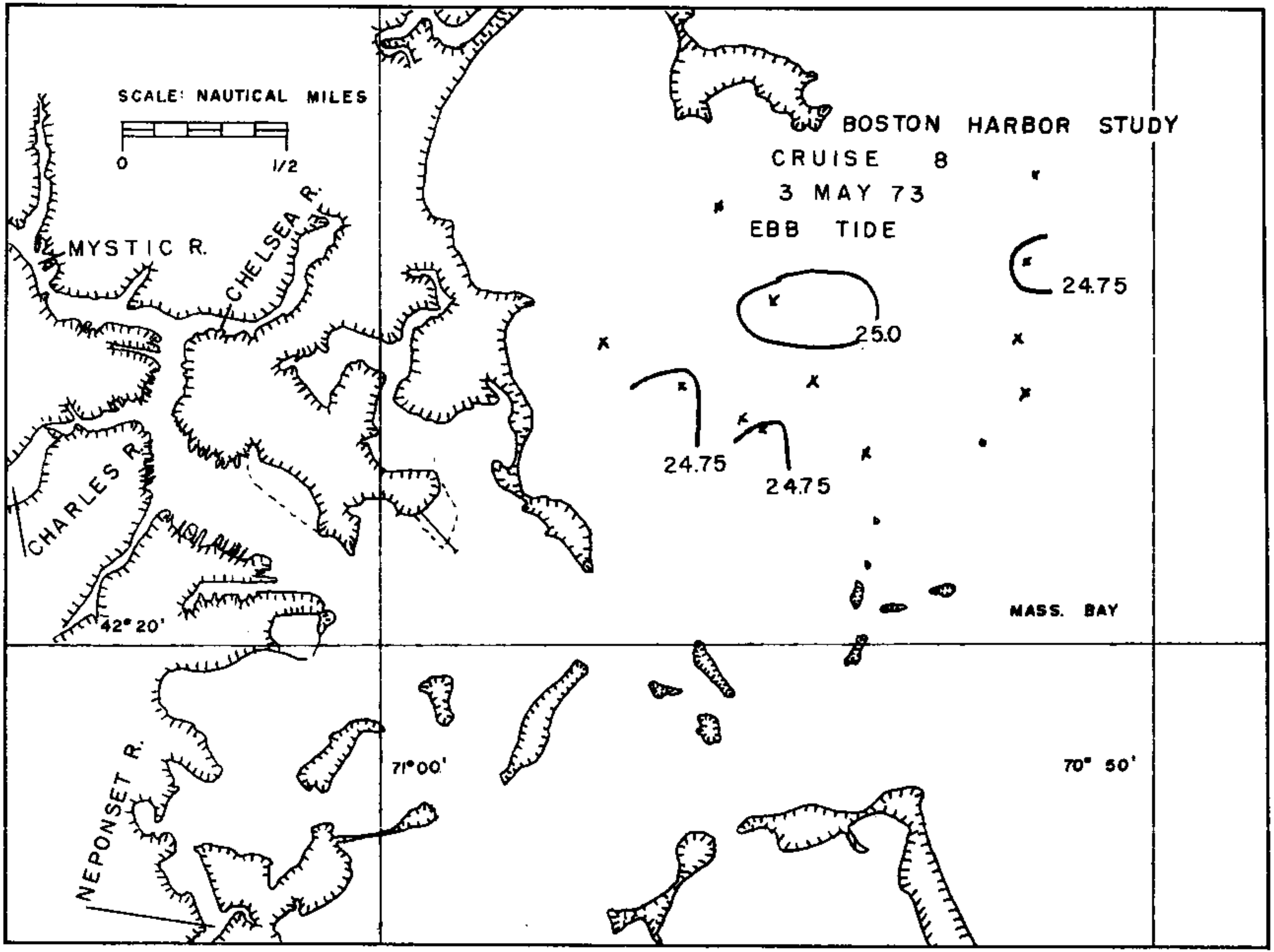


Figure 38 1.0 METER SIGMA-T

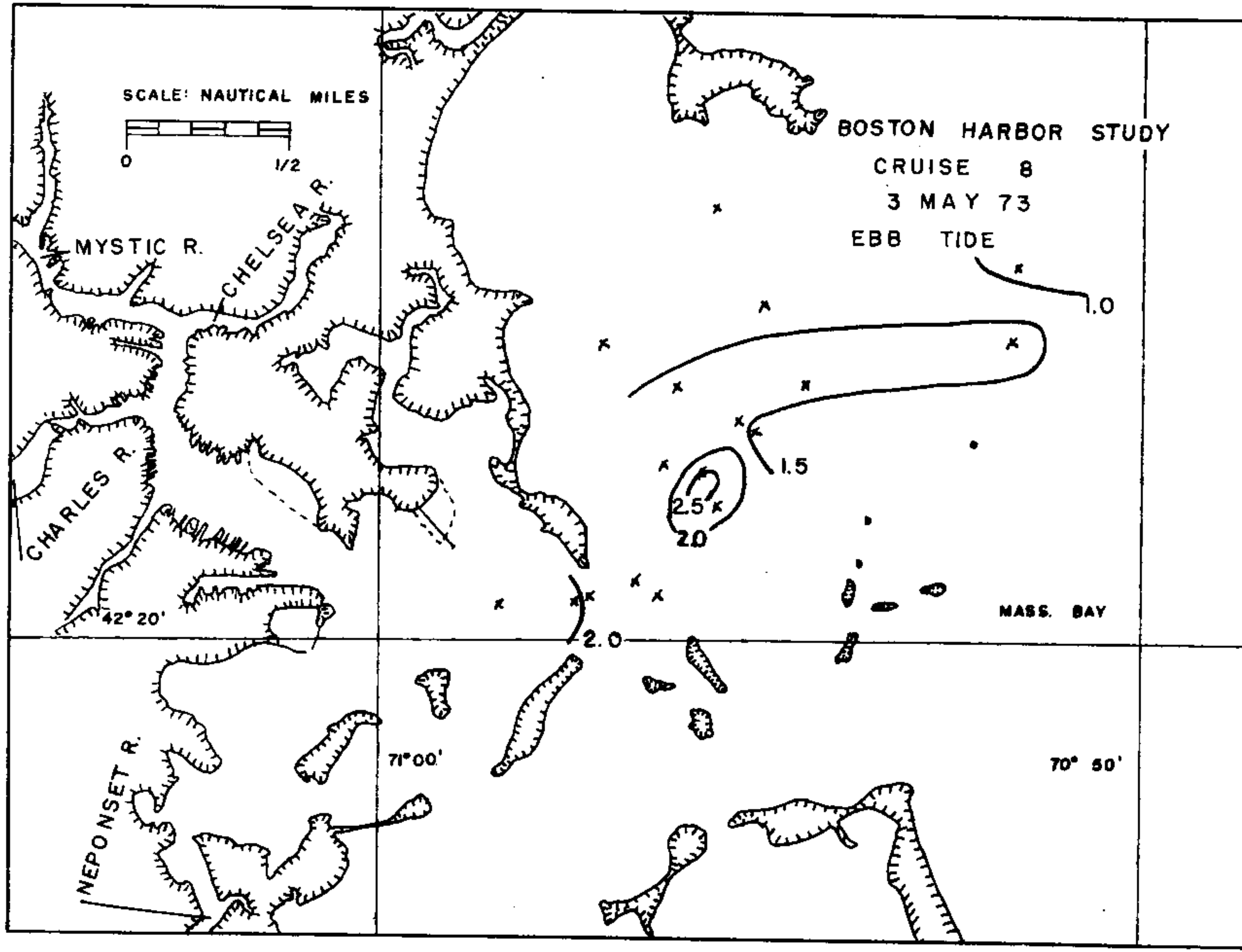


Figure 39 1.5 METER ORTHOPHOSPHATES in μgmatm./l.

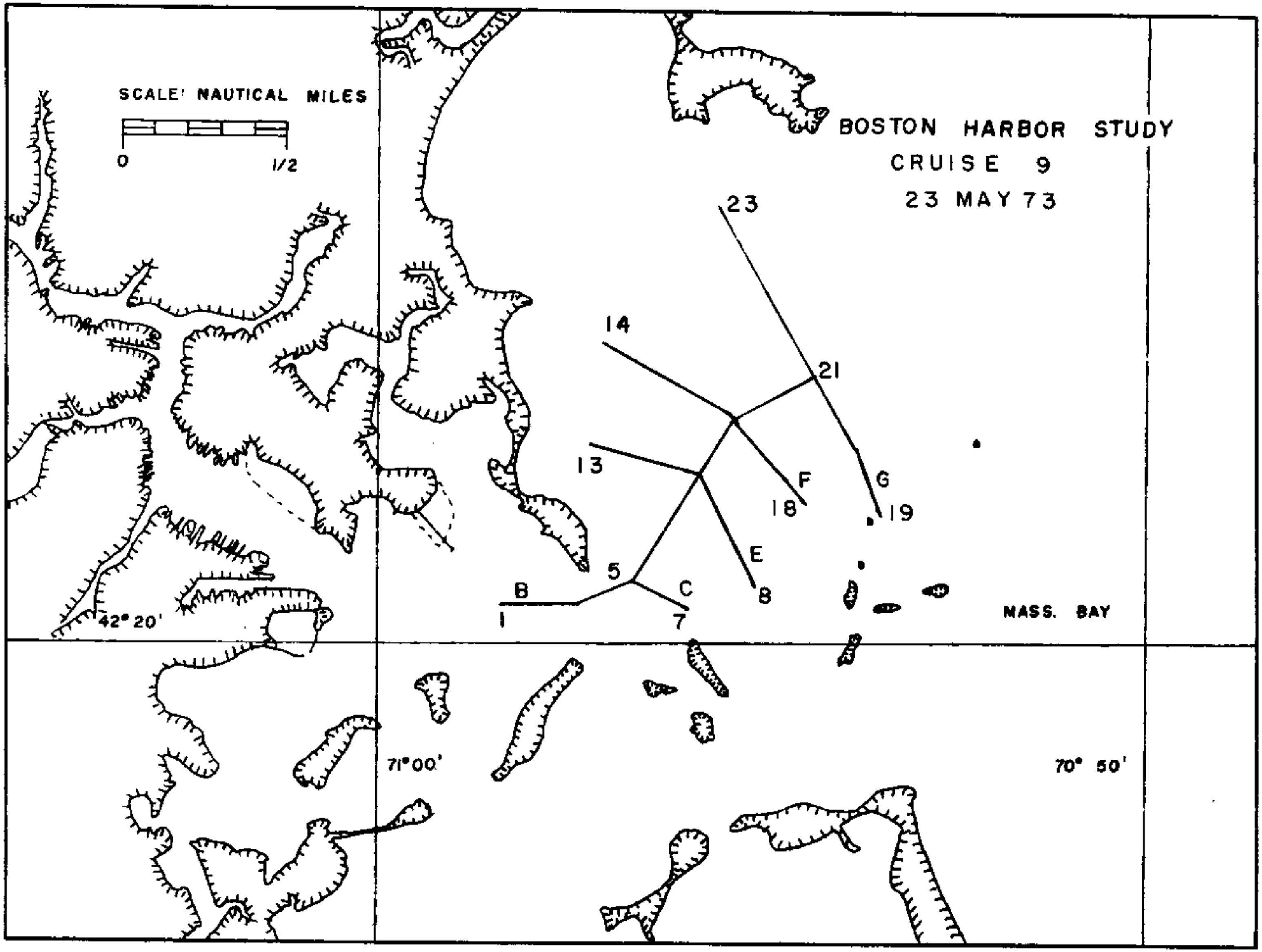


Figure 40 SECTION LOCATIONS . Cruise 9

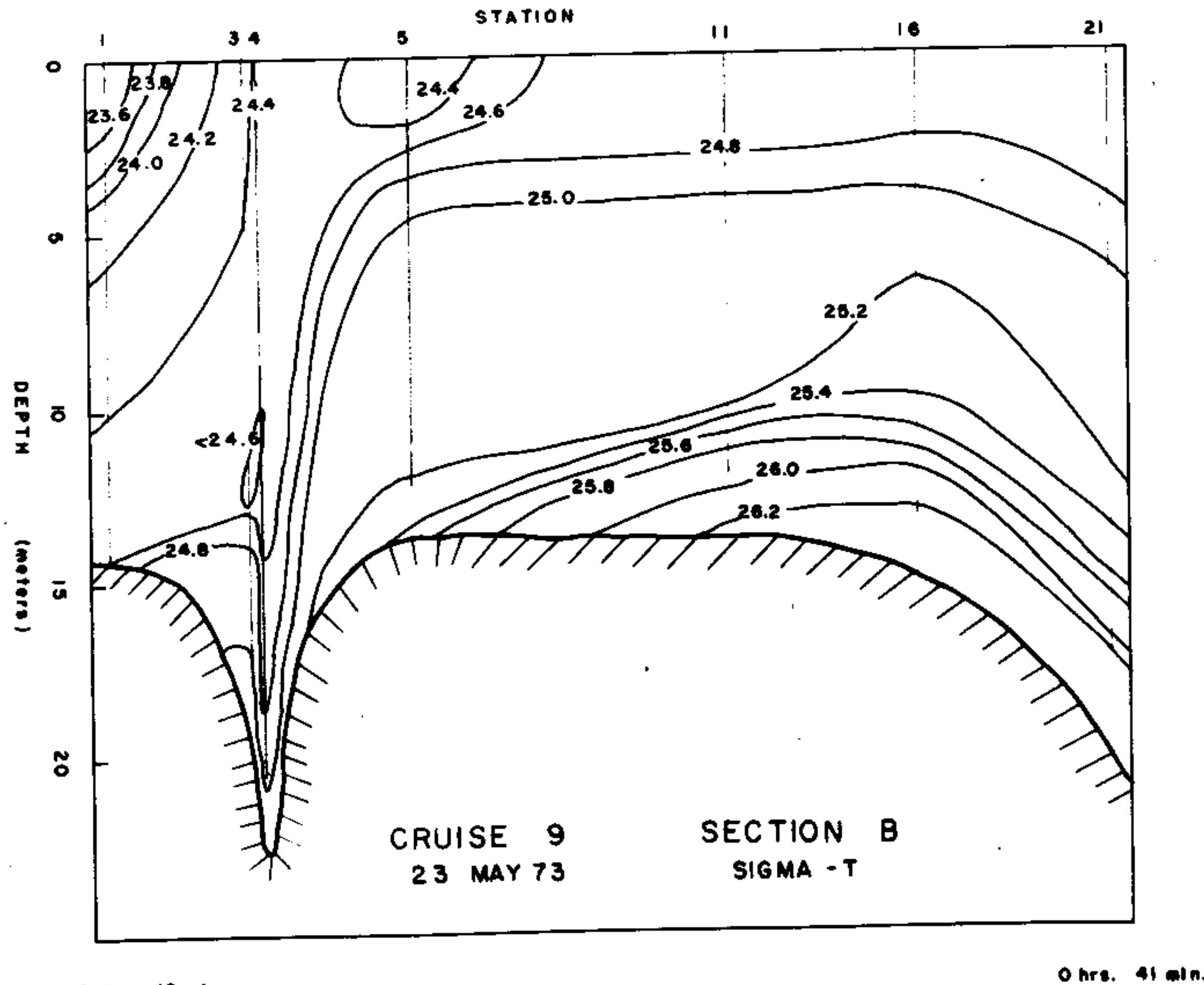
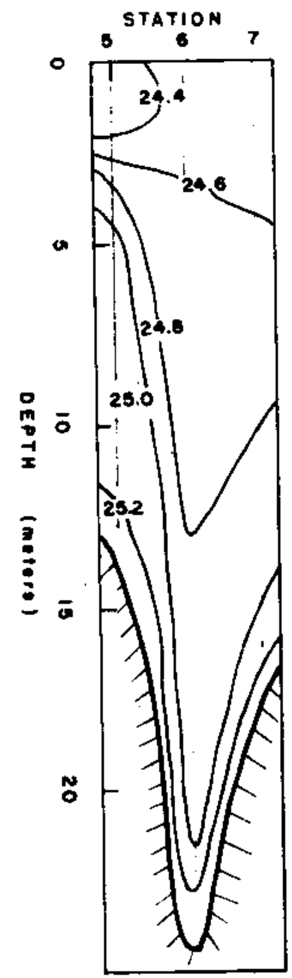


Figure 41 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters vertical distortion 250:1

CRUISE 9
23 MAY 73

SECTION C
SIGMA - T



10 hrs. 56 min. 11 hrs. 9 min.

Figure 42 Times refer to hours after high water, Boston. Scale; 1 cm. = 500 meters
vertical distortion 250:1

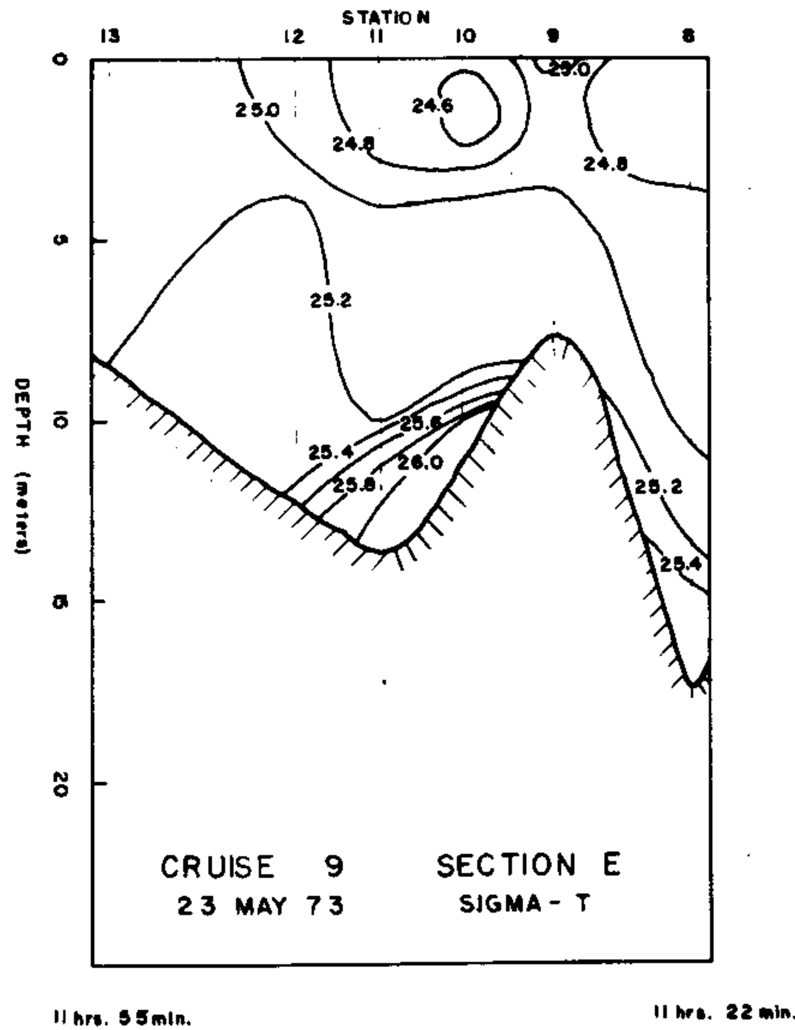


Figure 43 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters vertical distortion 250:1

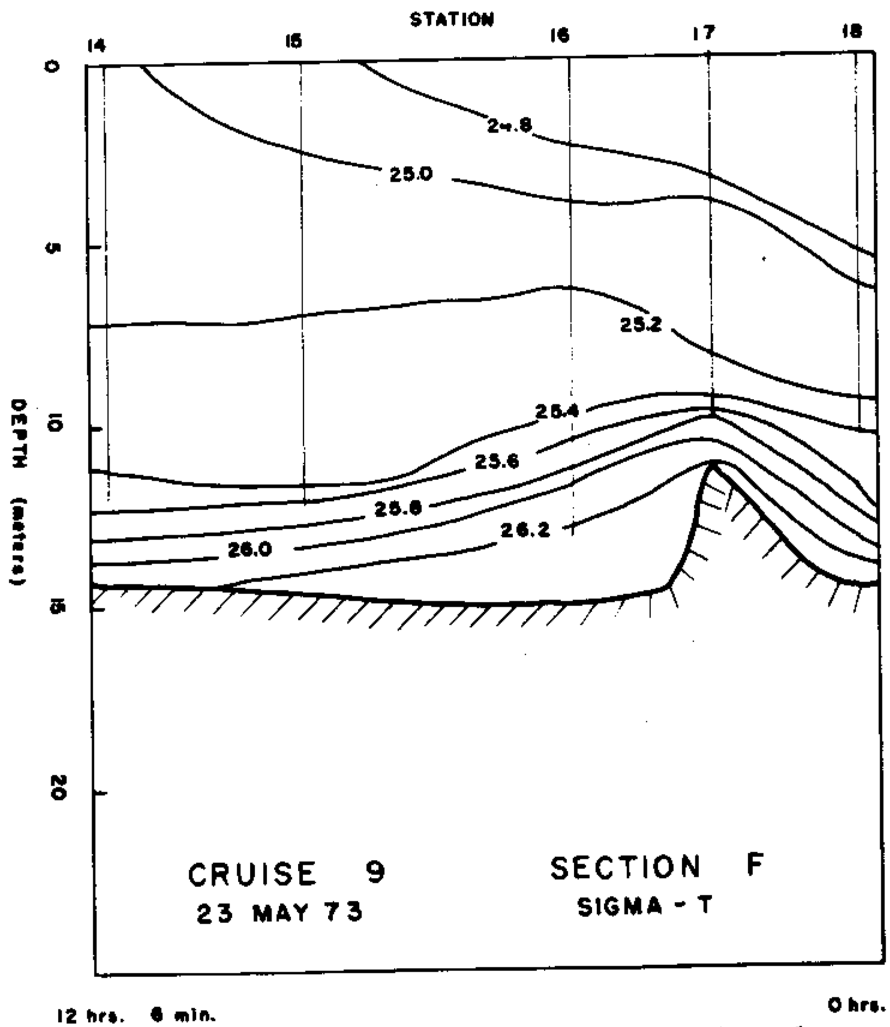


Figure 44 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters
vertical distortion 250:1

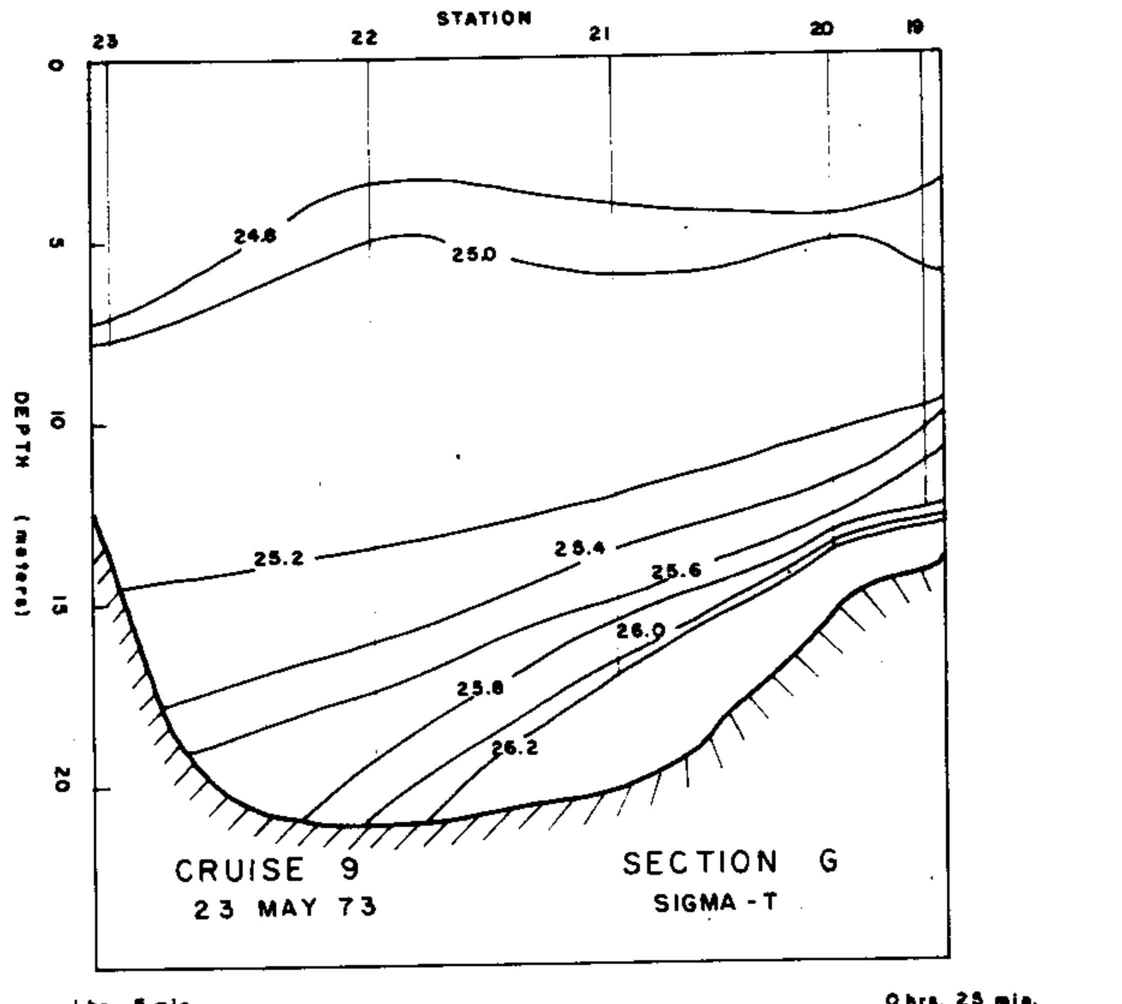


Figure 45 Times refer to hours after high water, Boston. Scale: 1 cm. = 500 meters
vertical distortion 250:1

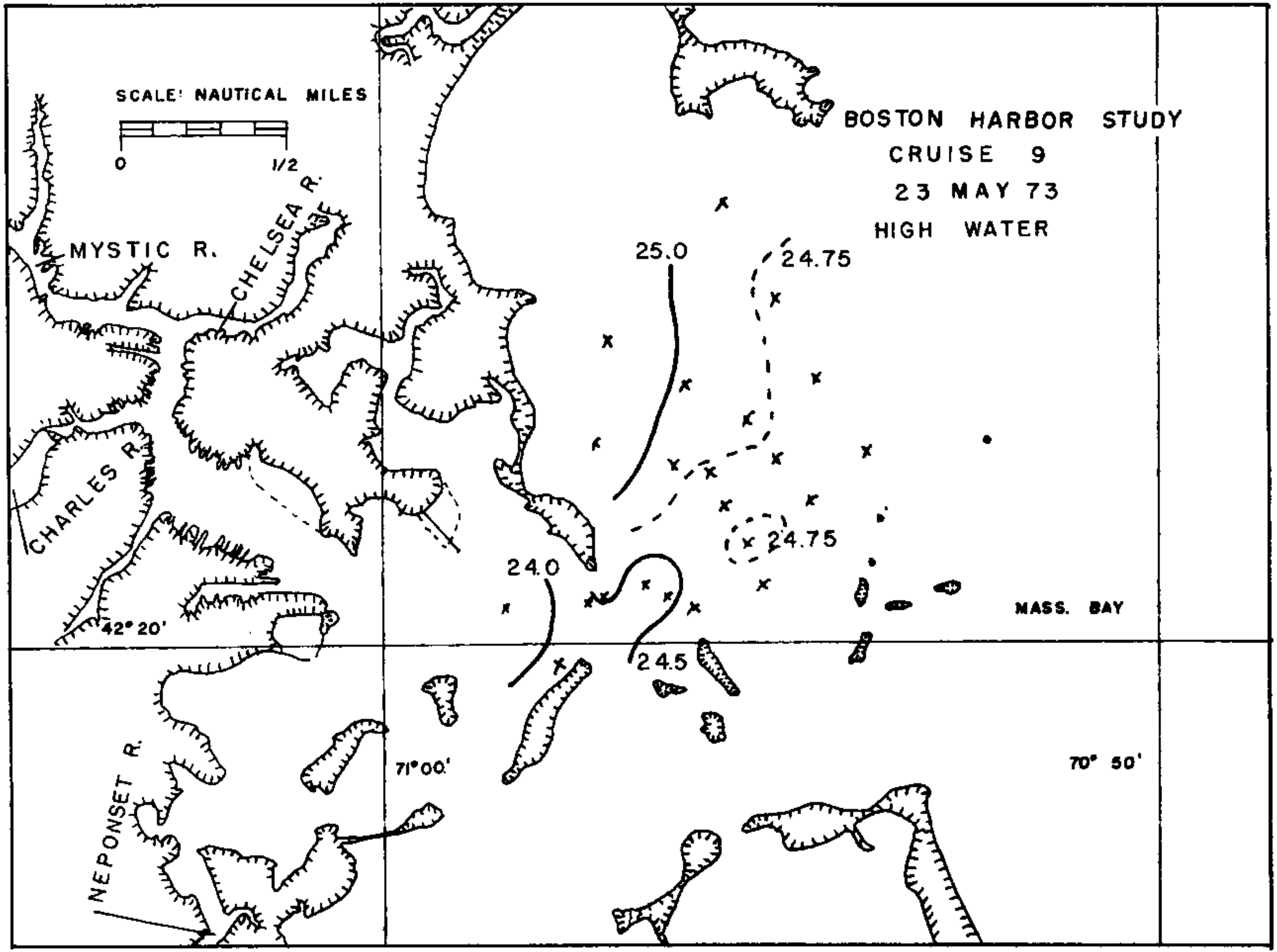


Figure 46 LO METER SIGMA -T.

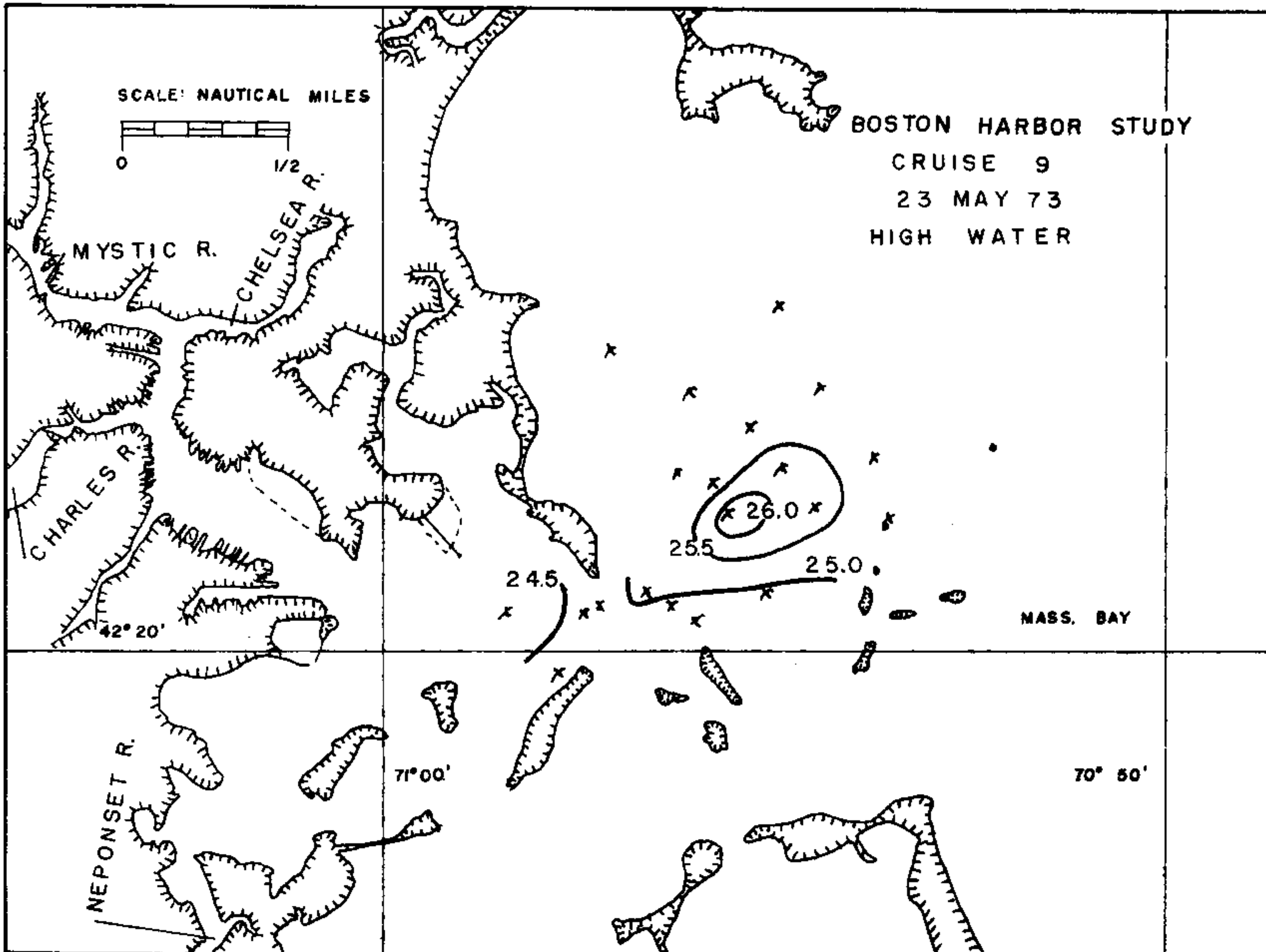


Figure 47 10.0 METER SIGMA – T.

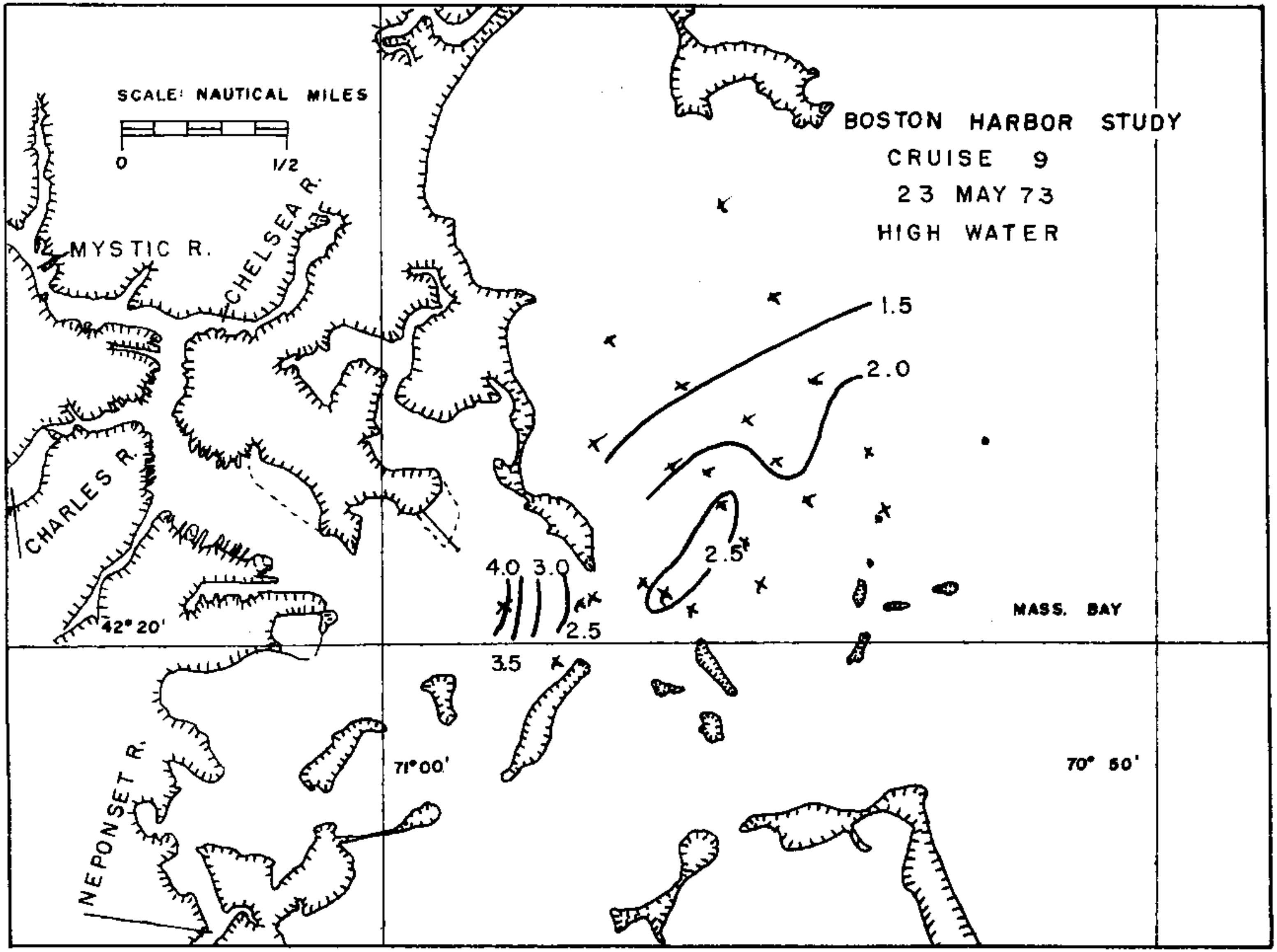


Figure 48 SURFACE ORTHOPHOSPHATES in μgm.atm./l.

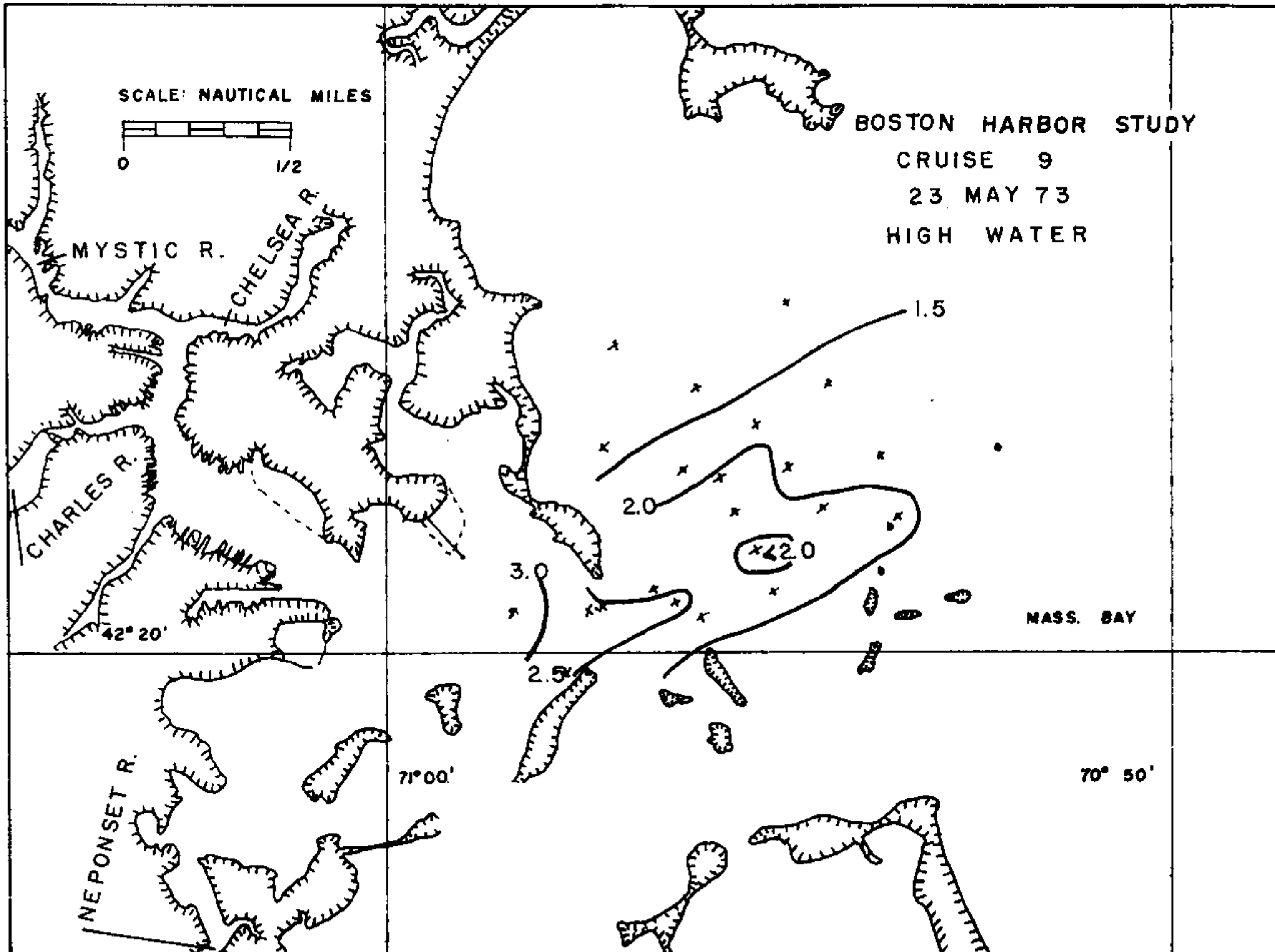


Figure 49 3.5 METER ORTHOPHOSPHATES in μgm.atm./l.

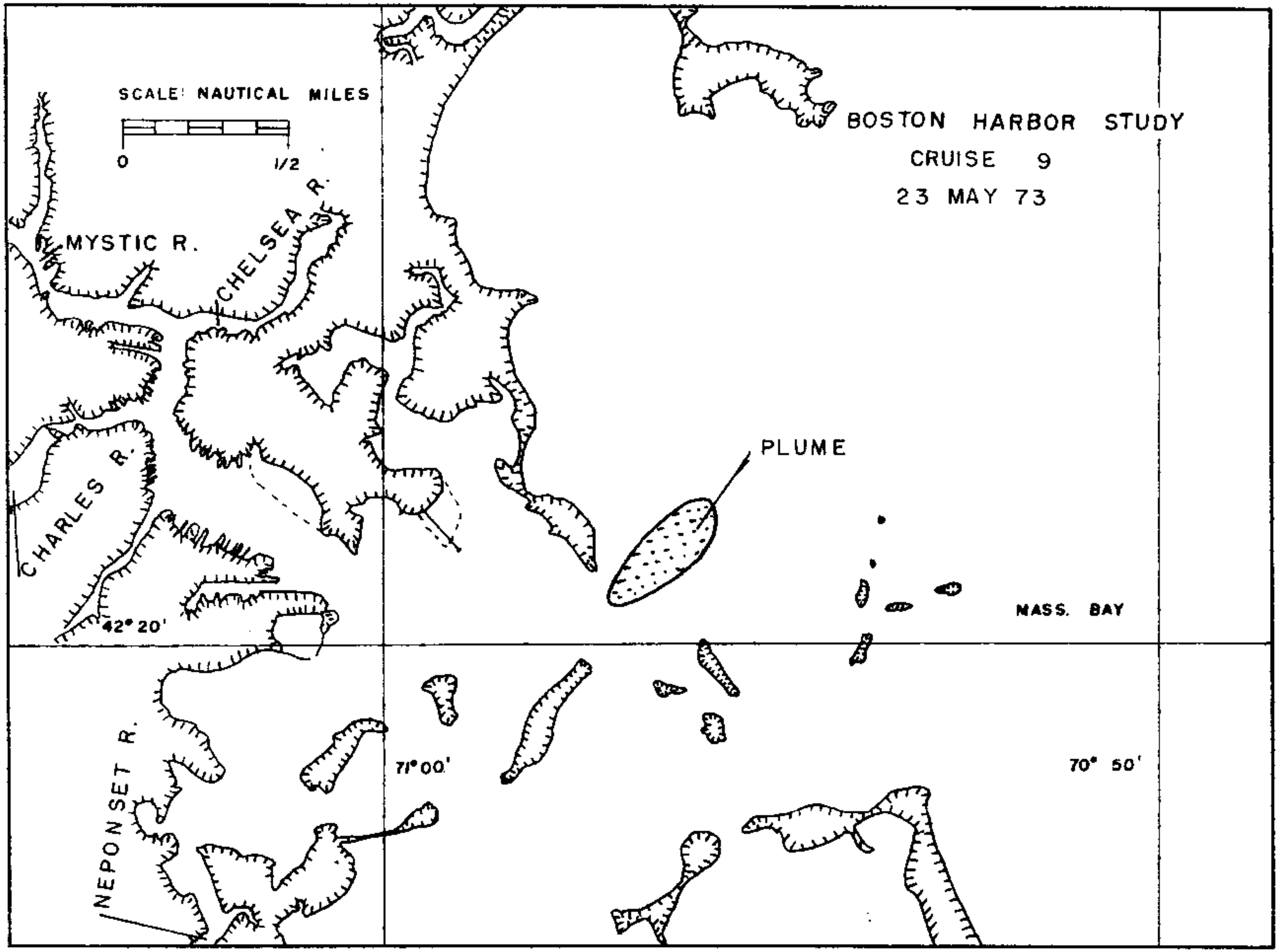


Figure 50 VISUAL OBSERVATION 1-1/2 hrs. into ebb tide

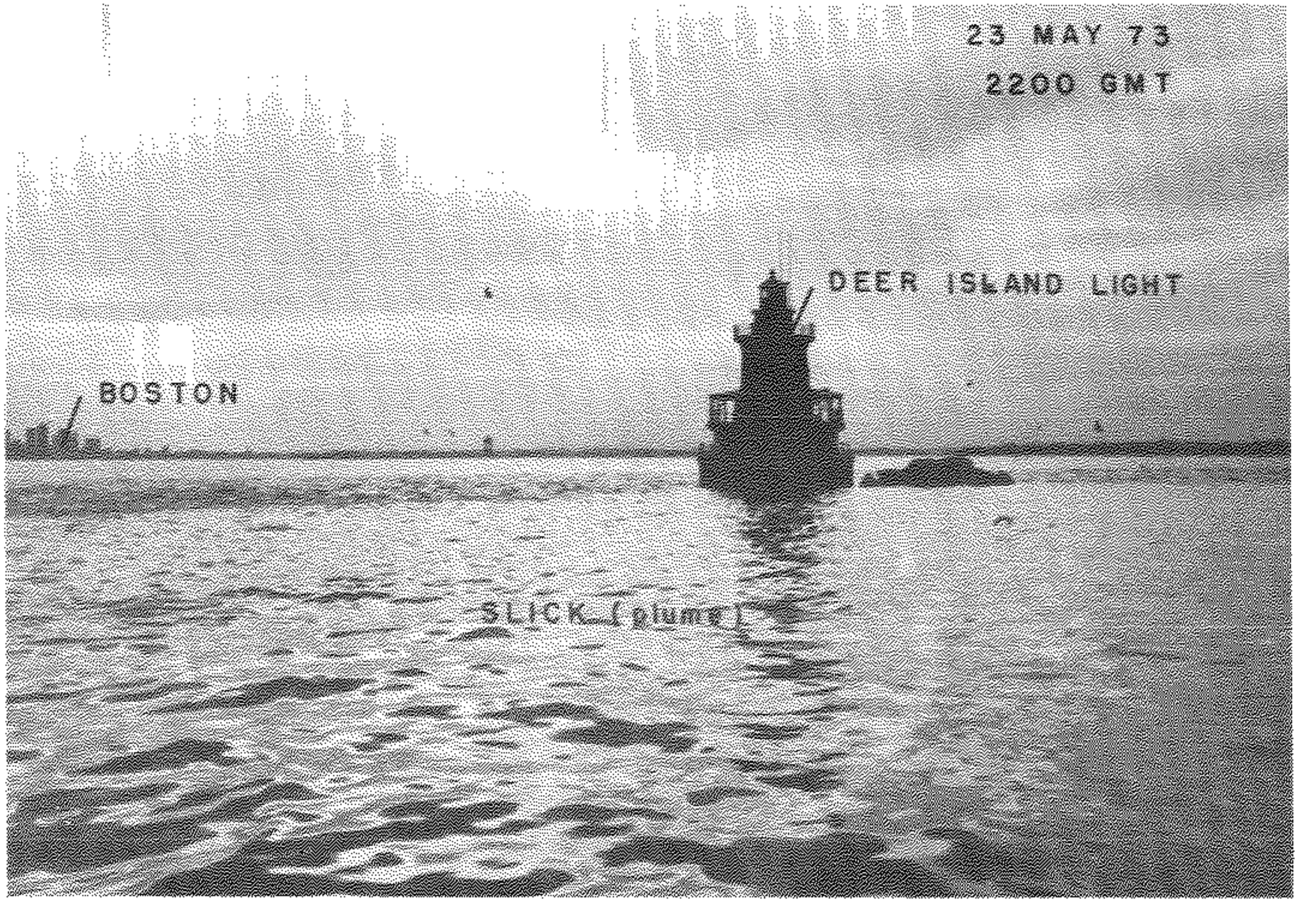


Figure 51 Cruise 9 Deer Island Effluent Plume 23 May 73

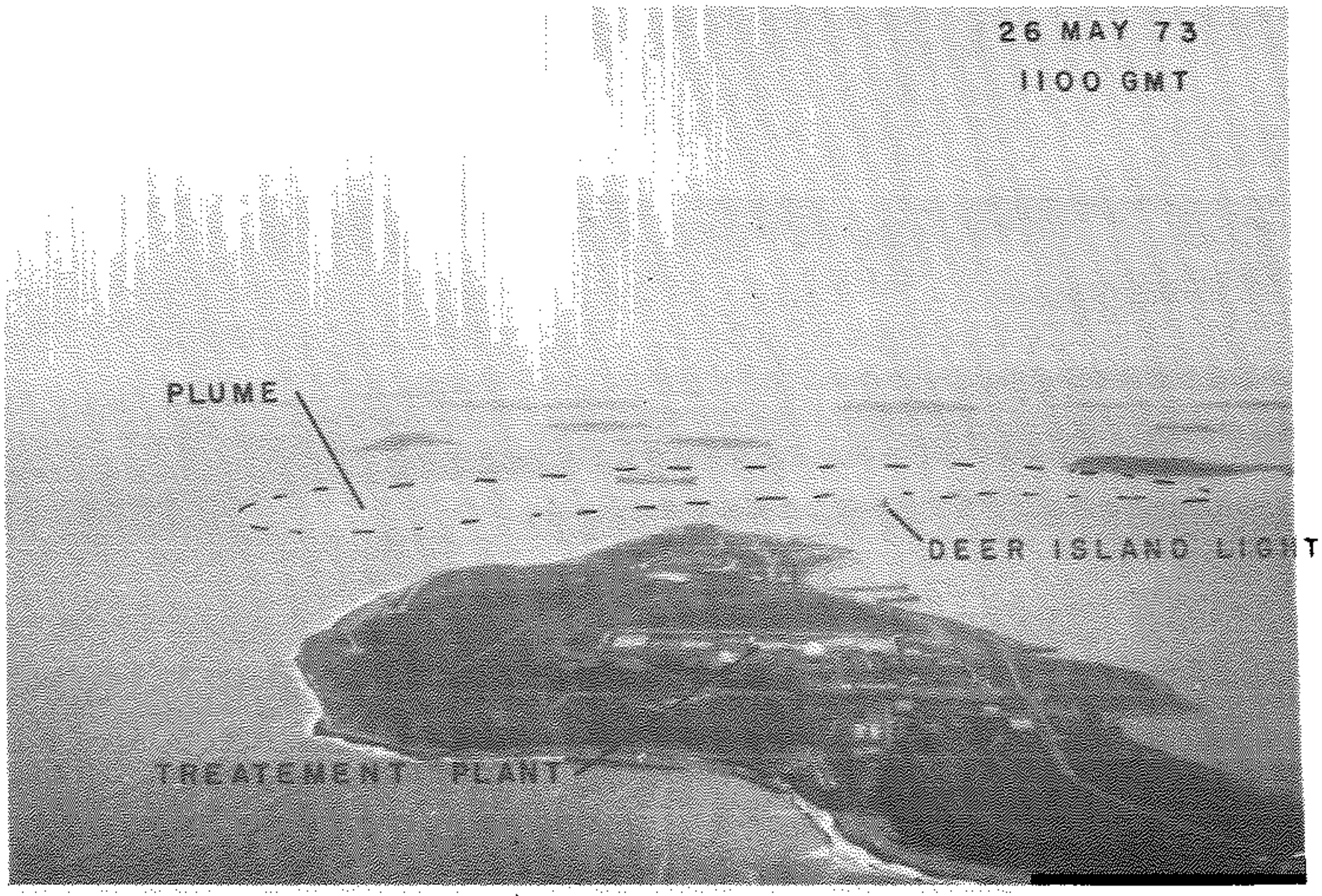


Figure 52 Aerial Observation of Deer Island Effluent Plume 26 May 73

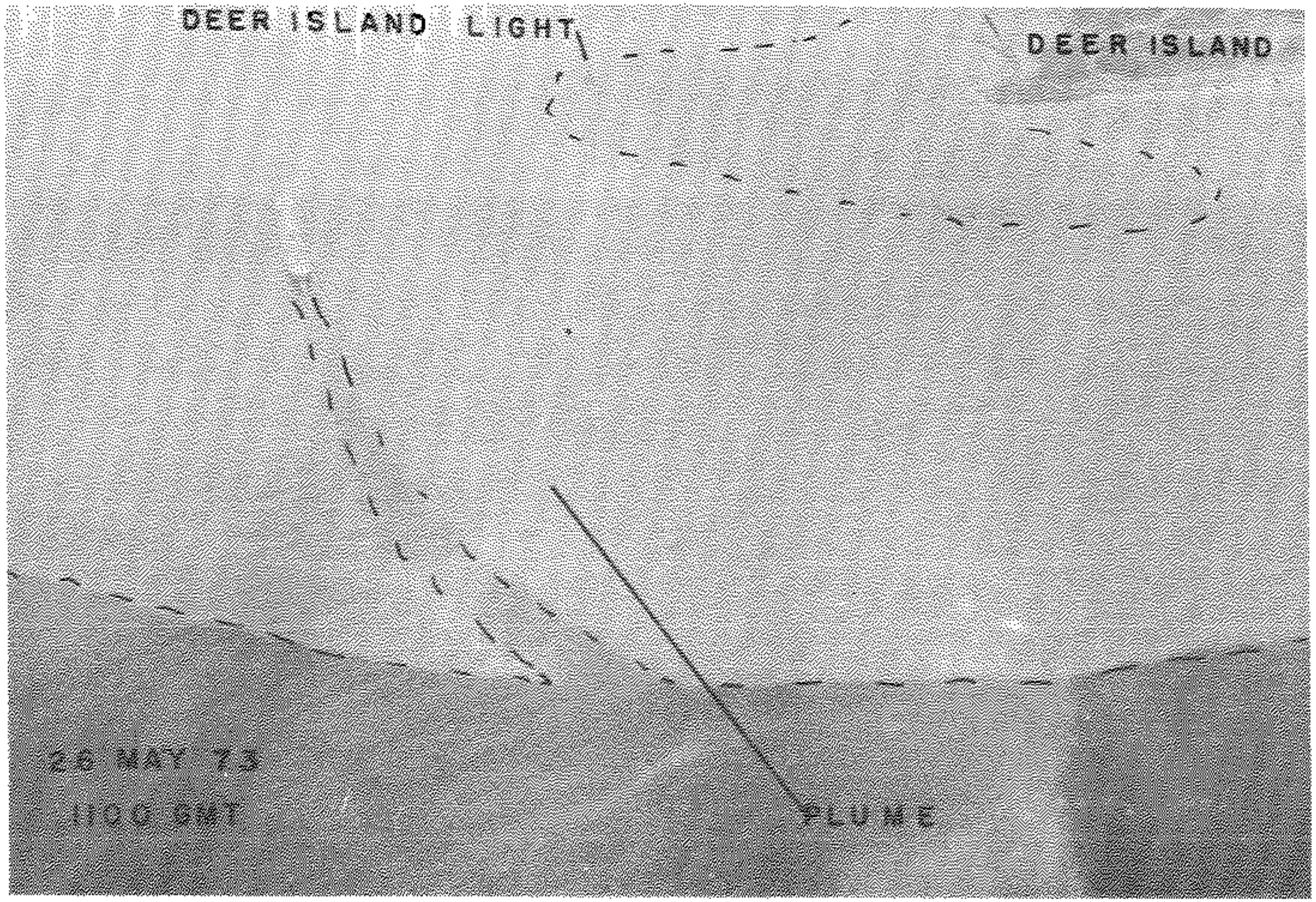


Figure 53 Aerial Observation of Plume with Freighter Wake 26 May 73

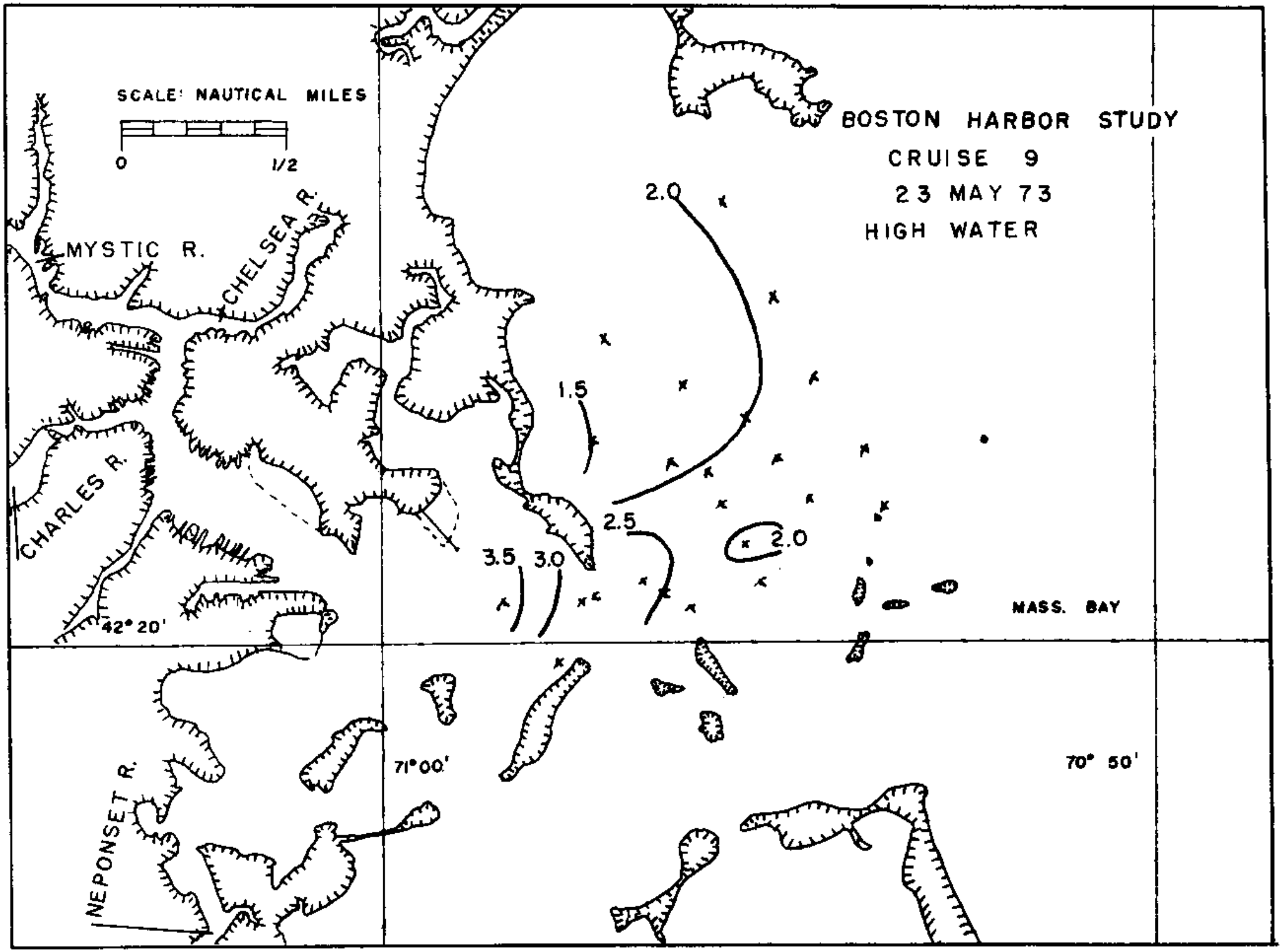


Figure 54 REGRESSION ORTHOPHOSPHATES in μgm.atm./l.